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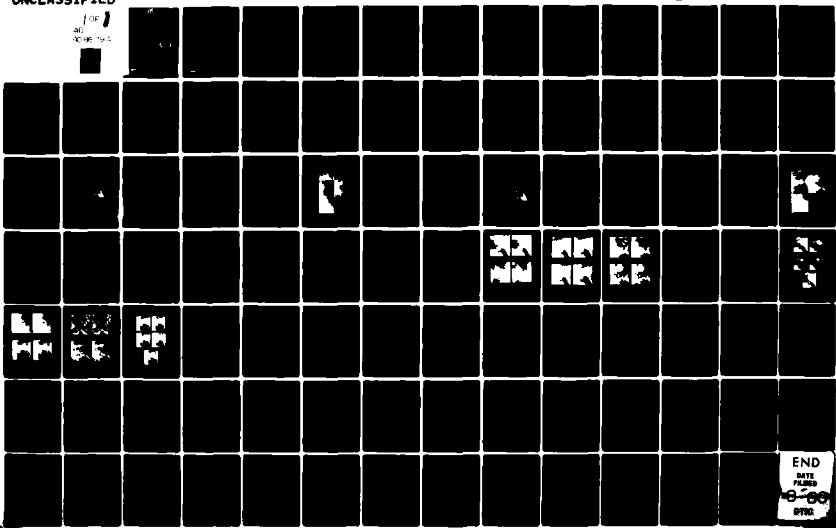

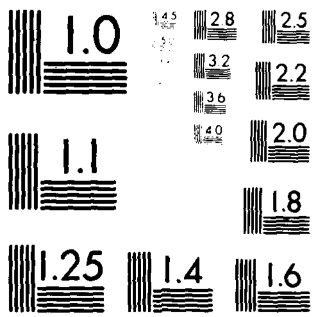
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ANALYSIS OF A TRIANGULATED IRREGULAR NETWORK (TIN) TERRAIN MODEL FOR MILITARY APPLICATIONS

By: HENRY A. OLENDER

Prepared for:

NAVAL ANALYSIS PROGRAM
OFFICE OF NAVAL RESEARCH
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This report describes a comparative evaluation of two digital terrain models (DTMs) in the context of tactical terrain analysis problems in Marine Corps ground combat operations. The two DTMs are the triangulated irregular network (TIN) model and the uniform rectangular grid (URG) model. The URG model represents terrain by simply encoding the terrain elevations on a uniform grid while the TIN model fits a series of irregular triangular facets to the terrain. The TIN is a surface-specific model because distinctive surface features, such as peaks, pits, passes, ridgelines, and valley-lines, control the selection of triangular facets. In

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general, fewer points (triangle vertices) are required to model a given surface with a TIN compared to the URG. Average digital data storage requirements are ~~hopefully~~ reduced, although significant digital encoding overhead must be included in the TIN model.

The comparative evaluation was performed by selecting several geographical regions of interest and two tactical test problems; the determination of visible ground areas from given observations points, and the determination of accessible ground areas to generic types of vehicles. TIN and URG models of the selected regions were then obtained and separately applied to the solution of the two test problems. Digital data base storage requirements, computer resources used, and problem solution performance measures were then compared. The most significant computer resource measure was CPU time, and the problem solution performance measure was defined as the areal measure errors in the resulting visibility and slope threshold maps. A high density, high resolution URG terrain model was employed as the "baseline" data base, and other lower resolution URGs and the TINs were employed for comparison.

PREFACE

This report documents the results of a comparative evaluation of two digital terrain models, the uniform rectangular grid (URG) model and the triangulated irregular network (TIN) model. The work was sponsored and monitored by Mr. James G. Smith (Code 431) of the Office of Naval Research.

The research was performed by the Center for Defense Analysis (CDA) of the Systems Research and Analysis Division (SRAD) of SRI International. In addition, Mr. James J. Little and Mr. Robert J. Fowler with Simon Fraser University in Burnaby, British Columbia, Canada served as consultants on this project to generate the required TIN models of selected terrain regions and to apply the TIN models to the solution of selected tactical test problems. Their assistance in this project was very significant and was most appreciated. Mr. Jan Kremers of the Artificial Intelligence Center at SRI also contributed significantly to this project.

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I INTRODUCTION

Digital terrain modeling (DTM) is concerned with the digital storage, analysis, and display of surface configuration data (X,Y,Z) for topographic mapping. The field of DTM is relatively new and growing. Many methods of DTM have been studied and applied to real problems, but two are of concern here: the uniform rectangular grid (URG) and the triangulated irregular network (TIN) methods. This technical report presents the results of an evaluation that compares the TIN and URG methods in the specific context of Marine Corps ground combat operations.

In applications, the URG is by far the more widely used method. Other names used for this method are regular grid, regular rectangular grid, elevation map, or simply grid. The concept is quite simple: store elevation data at uniformly spaced intervals in a rectangular coordinate system, and use interpolation at all other points.

The TIN methodology is a triangle-based system of DTM. The TIN method has been developed over the past several years by a group at Simon Fraser University (SFU) at Burnaby, British Columbia, under Professor Thomas K. Peucker.* The Geography Programs Office of the Office of Naval Research has sponsored much of the research.

The TIN concept is more difficult to describe succinctly than the URG concept. Basically, a portion of the earth's surface is approximated by a collection of connected triangles in (X,Y,Z) space whose vertices are chosen to minimize the total number of points required. Usually the points are chosen in an irregular manner, and many are points of high information content (such as mountaintops, streambeds, ridgelines). Such

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* T.K. Peucker, et al., "Digital Representation of Three-Dimensional Surfaces By Triangulated Irregular Networks (TIN)," Technical Report No. 10, ONR Contract NO. N00014-75-C-0886 (NR 389-171), Simon Fraser University, Burnaby, B.C., Canada, (1976).

points are called surface-specific points. The TIN is considered a surface-specific method.

It is not difficult to realize that a given accuracy can be achieved with fewer points with the unconstrained point selection of the TIN method than with the constrained point selection of the URG method. The number of elevation points that must be stored is only one of many things that must be considered, however.

The many steps involved in computer storage and processing as well as the preprocessing time and the cost required to put the data into the computer in the appropriate format are important factors that also must be weighed in comparing alternate DTMs.

The second major aspect of a comparative evaluation is the application. The question is, "Given that the methods have somehow been computerized, how well do they perform?" This question has been discussed in general for many years by workers in cartography, topographic mapping, geology, geodesy, and other fields that are concerned with representing and describing the earth's surface. There is no apparent general agreement concerning evaluation--a specific context seems to be required, and usually this is not available or is too narrowly defined.

The objective of this study is to address the question, "how well do two competing DTMs perform?" The present study differs from most of the other studies requiring comparative evaluation of different DTM methods because a specific area of application, Marine Corps ground combat operations, has been selected. Within this area of application, two specific tactical problems were selected for use as a basis of the evaluation: the determination of visible ground areas, and the determination of accessible ground areas.

In many respects this narrowing of the area of application makes determining the performance measures easier for evaluation than it is for the general problem, at least, if the measures are considered one at a time. It does not necessarily make the selection of a <u>composite</u> measure any easier, however. The evaluation primarily considers the measures individually and only qualitatively addresses the need for composite measures.

II EVALUATION METHOD

A. An Overview of the Evaluation Concept

The comparative evaluation of the TIN and URG methods consists of comparing computer resource requirements and performance measures for a suitably selected set of test problems on terrain that is representative of Marine Corps ground operations. This report defines the computer resources, the performance measures, and the test problems; selects a baseline for comparison; and develops a method for comparative evaluation. The geographic area is near Twentynine Palms, California, which fortunately provides the variety of terrain that is needed for evaluation. Following these topics, the results of the evaluation are presented and discussed and conclusions and recommendations are presented.

The baseline representing the "true" terrain against which both the TIN and URG methods were compared is itself a uniform rectangular grid with spacing that is closer than actually needed in the test problems. The surface-specific points for the TIN were selected from these closely spaced grid points. A series of URG models were evaluated in which each URG model consists of subset of points from the baseline grid; interpolation provided all other points. E.g., the first URG tested had a grid size twice that of the baseline so that it contained every other point in both the X and Y directions. The remaining points can be thought of as "held back" for purposes of evaluation. The other URGs had grid sizes four times and eight times that of the baseline. The evaluation of each set of URG models provides a series of points that can be used to plot graphically a computer resource measure versus a performance measure for a test problem solution. The TIN model evaluation provides a single point on such a plot. This method, then, provides the ability to compare directly the two models by analyzing the position of the TIN point relative to the URG curve. Further explanation of this baseline and comparability concept, which is central to the entire evaluation, is given in a separate section.

B. Test Problem Areas

Two types of test problems from Marine Corps ground combat operations were selected for the evaluation. The first is the problem of line-of-sight (LOS) observation and the second, the problem of trafficability. These problems directly relate to such tactical problems as air defense, fire support, accessibility, and helicopter operations.

In air defense, the main considerations, for either the selection of a radar or the estimation of detectability of low-flying aircraft for a given site, are radar masking and clutter. In this case, both problems are essentially the same: they are one-dimensional (area) problems, equivalent to the LOS observational problem.

Fire support problems involve both observation and weapon trajectory considerations. For observation, a DTM should be able to predict whether an observer at Point A can see a target at Point B and relay the target information to weapon firing from Point C. Trajectory prediction is also required to see whether a weapon of a given type (ballistic) can reach the target or whether the terrain masks the target. Although each of these fire support problems is one-dimensional (i.e., the DTMs must estimate a profile along the line of bearing from one point to the other), each can be embedded in the two-dimensional problem obtained when all lines of bearing from a given point are considered.

Questions of accessibility or mobility of this sort are: "Can a vehicle of a given type (truck or tank) get from Point A to Point B?" i.e., "Is Point B accessible from Point A?" This is another one-dimensional problem for the DTM, in which a "trial" path (in X,Y coordinates) must be specified and the profile along this path calculated from the DTMs. The analysis of the profile answers the question of accessibility. However, an alternate approach for solving these types of problems is first to solve the two-dimensional terrain trafficability problem, which provides information for the selection of paths that are feasible for each type of vehicle.

A final class of problem stems from the need for finding safe corridors for helicopters during vulnerable periods of flight. These problems involve LOS considerations from one or more enemy observation points.

Thus, the solution of the two-dimensional LOS observation problem, and the terrain gradient problem provide partial solutions to each of the tactical problems outlined above. For this reason these two problems were selected as test problems for the comparative evaluation of TIN and URG terrain models.

C. Measures for Evaluation

The measures that were used for evaluation are of two kinds: measures of computer resource requirements and measures of performance. For a given computer system installation, a computer resource measure may be considered already known: the numerous processing time and storage considerations are weighted and aggregated by the pricing algorithm of the particular system; the measure is dollars. Here, the problem is not so simple, however. We want computer resource measures that will permit estimation of resources for a variety of systems, large and small, with different central processor/mass storage configurations. We want measures that are as independent of any particular system as possible and that do not necessarily use dollars. The principal components that were identified are storage requirements for the evaluation points, auxiliary data, and algorithms needed for processing, storage accesses, and the number of basic computer operations.

Performance measures are necessarily dependent on the kind of problem. Area problems tend to have binary qualities, e.g., for a given radar site and antenna height, any given point is either masked or it is not. Thus one can solve the LOS observation problem and calculate, for each DTM evaluated, a map showing masked (or conversely, unmasked) points. This map can be compared with a corresponding map showing the true (baseline) terrain. Two kinds of differences in the maps will be found; areas that are truly* masked will occasionally be shown as unmasked by the DTM, and parts of the areas that are truly unmasked will be shown as masked. Using the terminology of statistics, these differences can be considered Type I and Type II errors, respectively.

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* According to the baseline.

Two performance measures can be immediately defined for these situations: Measure 1 is the areal measure of the Type I and mesure 2 is the areal measure of the Type II area. The sum* of these areas, which is simply the area of the region where the DTM method was in error, is a third measure.

A measure for the accessibility problem can be constructed along the following lines. If a definite criterion determines for a given elevation profile whether a given point in the terrain can be negotiated by a specific type of vehicle, then the DTM will provide a binary answer, namely, whether that point can be traversed or not. The DTM answer can be correct or incorrect according to the baseline. Errors of Types I and II are again possible: traversable points can be called nontraversable, and vice versa. One criterion (but not the only one) for making the traversable determination is the maximum slope along the profile: if the slope is less than a specified constant for a particular vehicle, the point is considered traversable, otherwise it is not. The map of all traversable terrain points forms a solution to the terrain gradient problem and indicates which paths (if any) can be used to go from one point to any other point in the region of interest.

Thus, the measures of performance for both the LOS observation problem and the terrain gradient problem are taken to be the areal measures of Type I and II, and the sums of these measures.

D. Terrain Representation

A basic consideration in the evaluation is, "What criteria should be used for fitting a DTM to the test area terrain? For a TIN, ideally we would like to know first the accuracy requirements of the ground combat problem; these would be found by analyzing the tactical situation and determining what is required of a DTM for that situation. Knowing

* Type I and Type II errors will vary in relative importance from problem to problem. Weighted sums, rather than the simple sum of the measures will generally be more appropriate where a clear rationale for the selection of weights is available.

the accuracy requirements, we would then introduce them into the specific point-selection and triangulation algorithms that fit the TIN.

In the evaluation, we must approximate this idealized approach because accuracy requirements are difficult to determine and the "controls" available to fit a TIN are uncertain.

Other concerns about the TIN fitting also bear on evaluation philosophy. Available fitting methods are partly heuristic, and even the automated parts do not have parameters that permit precise control of fitting errors. Moreover, the accomplishment of a single TIN fitting is a significant task, and there was little time for the trial-and-error methods necessary to improve each fit.

Therefore, we designed the evaluation so that it does not depend critically on how well the TIN fitting is accomplished. Having approximated the ideal fitting approach as well as possible, we will accept the resultant TIN as a black box: we will simply use it in test problems and accept whatever fidelity it may have to the real surface. The fidelity will show up in the outputs (such as the visibility maps) when we compare them with corresponding outputs from the baseline.

For the URG, the surface-fitting situation is different. In one sense, the URG method is considerably more flexible than the TIN method because several different methods for defining an URG from the dense grid baseline may be considered. One may, for example, choose every other baseline point or every fourth point to define a new URG. An entire family of URGs can be defined from the single baseline URG, the members of which have different grid sizes, so that the URG family can be considered a continuum. We need this continuum in our approach to evaluation to be able to compare the DTM methods.

E. Comparability of DTM Methods

Several available measures characterize the important aspects of the problem, but they are essentially independent of each other and, therefore, irreducible in number. Corresponding measures agreeing for one aspect of the problem usually disagree everywhere else. A reduction in dimension is needed.

Assuming that there are only two measures, one for computer resources and one for performance, the problem becomes: "How can one of these measures be eliminated?" The answer is that the URG spacing must be varied continuously until the values of one measure agree exactly. The remaining measure should directly reflect the performance of the DTM methods for the given test problems, because everything else has been made comparable. This approach proceeds as follows.

In contrast with the TIN method, which uses a single representation for the entire evaluation, several URGs are analyzed. Each URG candidate is defined as a subset of the baseline grid points by a regular relationship such as every other point in X and Y separately, or every third or fourth point. Thus each URG has a specified spacing that is a multiple of the baseline spacing.

Another important feature in the evaluation is not, strictly speaking a feature of the baseline. In approximating the earth's surface in the terrain test area, we only allow the URG to have points that are a subset of the baseline points. (This is in contrast to the TIN, which has access to all the baseline points). The URG is then forced to interpolate the remaining points, just as the TIN interpolates. (Linear interpolation is employed for both DTMs). The outputs that the URG generates depend on the points to which it had access and the method of interpolation. The same is true for the TIN, which has access to all of the points.

The question arises whether this method introduces a bias toward one of the DTMs. We feel that it does not. TIN can only employ a continuous map for its point selection, but, because the baseline grid is dense, each surface-specific point selected from the continuous map has a grid point in the baseline not far away. Thus, the TIN approximation is very close. The essential point to note is that the TIN chooses as many points as it likes to triangulate and fit the surface, but it must incur penalities in the computer resources. The situation is similar for the URG: finer grids should give better outputs, but use more computer resources.

The evaluation concept can be clarified by describing a hypothetical situation for which there are two contenders, one advocating TIN, the other advocating URG, and an unbiased evaluator. The evaluator has determined the terrain test area, the ground combat problems to be considered, the kinds of tactical variables, and the maps or other displays that are needed in these problems. Moreover, the measures of computer resources and performance are both defined by the evaluator. All this information is given to both the TIN contender and the URG contender so that they can design their best products for submission for testing and evaluation.* They are both given the baseline grid as well. Other relevant considerations, such as relative weighting of the different ground combat problems or tactical variables, may be ignored for this exposition.

Is this information sufficient for the contenders? Should they know how good the fit to the surface must be? Not according to the evaluation method given here! Performance measures are computed by comparing the contender's respective outputs with those of the baseline; none of this depends on how well the approximate surface has to fit the actual surface. Improved fits will always result in improved measures, but the improvement may not have practical significance.

The TIN contender is guided in his search for surface-specific points by knowledge of the evaluation; he knows that the more points he chooses the more penalties there will be for computer resources. In principle, the selection of points could be made into an optimization problem and be purely mechanical. A family of TIN solutions could be found: for each hypothetical amount of computer resources, one would choose points that optimize the performance measures. But which member of the hypothetical family of TIN approximations, all of them optimized, should be selected? The answer, in general, depends on how computer resources measures and performance measures will be traded off. To make all this precise would be difficult and would involve weighting

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*Actually, the URG contender has nothing to do--there is no choice left to him. The contender viewpoint would be more symmetrical if URG were replaced by some other more complex DTM method.

Type I and Type II errors and the relative importance of the different tactical problems. Given full and precise statement of the problem, optimization could, in principle, be carried out. A reasonable and realistic rationale for the TIN approximation is that it should only satisfy the accuracy requirements of the ground combat problems to the extent that these requirements can be determined.

The logical possibilities that may be encountered in making the comparisons are shown in Figure 1. Recall that we have defined our performance and computer resource measures so that small values are preferable to large ones. Consider the test problem and terrain as given. For the single TIN approximation, a pair of numerical values, one for each measure, determines a single point, X, in the diagram. Similarly, any one URG determines a single point. By varying the grid spacing and interpolating between them, an entire curve is determined.

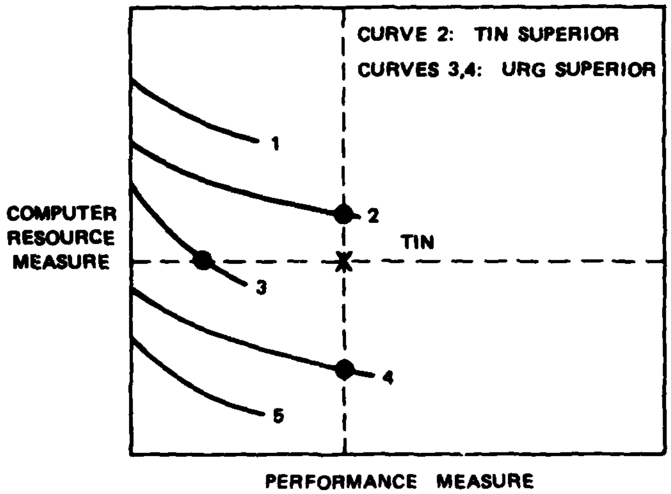

FIGURE 1 COMPARABILITY PLOT

Figure 1 shows the possible types of curves that may occur. Notice that all URG curves start at the computer resource measure axis because performance measures (errors of Type I and II) have zero value for the baseline URG. For each of the URG curves, the grid spacing increases from left to right. An increased spacing should degrade (increase) the performance measure and simultaneously reduce the computer resource

requirements. The URG curves, therefore, are expected to have the shape indicated. There are five ways that a curve may be traced out in the aggregated performance measure plot. In Cases 2,3, and 4, TIN and URG are comparable for one measure. In Case 1, the methods are not comparable: URG performance is always superior to TIN, but it also always requires more resources. Case 1 is considered unlikely because a sufficiently sparse grid should perform more poorly than any reasonable TIN. In Case 5, URG always out-performs TIN and always uses fewer computer resources. The URG method is clearly superior here, but this case is also considered unlikely for the same reason. We, therefore, expect to be able to compare the TIN and URG methods by varying the URG grid size. We should be able to derive a curve resembling Curves 2,3, or 4 for each problem.

F. Limitations of Evaluation Approach

The evaluation approach has several limitations. First, the number of terrain types and the number of test problems are small. For each given terrain/test problem, only a few military problems (tactical variables) can be considered; their measures are limited in number. These limitations are inherent in any problem for which no "global" theory is available. We can only choose representative problems as test cases.

Military needs in a particular ground combat contenxt present limitations of a different type. It is likely that a highly precise terrain represenation is not required in some problems. Sometimes a "caricature," somewhat analogous to a tourist map, is adequate. In those instances, our evaluation methodology may be biased against one DTM method because the method has no explicit parameters for specifying the requirements of problem accuracy. It is fairly clear that TIN, the basis of which is irregular points, should better represent a caricature of the terrain. The evaluation approach may, therefore, be somewhat biased against TIN.

The baseline concept involves two assumptions: (1) the dense grid data are error free, and (2) some points are whitheld from the methods so that evaluation can be made on these points. The "point-witholding"

assumption does not appear to be limiting. The "error-free" assumption is not thought critical because we are concerned with a relative problem (TIN versus URG) and not an absolute problem. Sample calculations show that errors in the elevations of the baseline grid tend to influence TIN and URG equally; their consequences will, therefore, tend to cancel out when comparisons are made. That is, the performance measures would be only slightly changed if the true elevation values were available.*

*This assertion can be tested by sensitivity analysis. The baseline terrain elevations can be altered slightly (randomly or systematically) by pseudoerrors with magnitudes similar to those of the errors in the baseline. Measures can then be calculated for the perturbed baseline and compared with the baseline. Time and funds did not allow the performance of such a sensitivity analysis.

III TEST PROBLEMS FOR EVALUATION

The TIN and URG methods are evaluated by examining their resource requirements and performance in representative ground combat operation problems of the Marine Corps. Several problem areas were defined and analyzed to determine whether they need topographic information and what they require of a digital terrain mapping system. As a result, two common types of problems were identified and selected as test problems for the evaluation.

The criteria for selection of test problems were:

- The test problems should be important to the Marine Corps in ground combat operations.
- Test problems should evoke questions that have quantitative answers that are realistic. A sample test problem that we would not include is one in which a map reader must look at the surrounding terrain and determine his location from a DTM-generated map. A complex pattern recognition process would be required for this task and would lead us far afield from this study.
- A variety of terrain types should be called for by the problem.

Problem areas considered were air defense, fire support, accessibility by ground vehicles, and safe corridors for helicopters. The identified test problems are the LOS observation problem and the terrain gradient problem.

A. Tactical Problem Areas and Test Problems

1. Air Defense

Air defense problems will arise in most significant areas of Marine Corps operations.

In past in-depth studies at SRI International, the dual problems of air defense and aircraft survivability considered LOS the principal tactical variable. Some of these studies have been reviewed for

applicability. LOS entered these problems in the form of "the distribution of defense/offense intervisibility segments" found by analysis of aircraft characteristics and tactics and interaction with the defense weapons. As the nature of the LOS became understood, the defensive system characteristics were introduced and survivability and attrition computed. Results were fed back into the problem to suggest a new radar site or changes in defensive siting doctrine.

These studies show that the major consideration in air defense is selection of the radar site. The problem of site selection is primarily influenced by masking and clutter effects. If a target is masked by some portion of the terrain, the radar will not illuminate the target and thus not detect the target. Similarly, even if the target can be illuminated by the radar, the ground clutter return over a given area may preclude target detection in that area. Thus, problem elements of air defense include determination of areas on the map surrounding a potential radar site that are masked/not masked for given target and antenna altitudes; and that have high clutter/low clutter* for a given antenna height. The latter problem requires information concerning the type of ground surface in addition to simple terrain data.

2. Fire Support Coverage

Several terrain-related mapping problems arise in fire support questions, planning, and analysis. Essentially, they involve LOS (for observation) and trajectory (for weapon firing) considerations. Because of the extreme variety of fire support problems, only representative situations and tactical variables can be examined. There are two fundamental kinds of mapping problems involved: fire coverage problems and observer-to-target LOS problems.

*Binary clutter levels can be obtained by specifying a threshold of clutter power that allows detection with a given probability and false alarm rate.

- For a hypothetical weapon and location in the terrain test area, a map showing points that are covered from the weapon location can be calculated and displayed. This map shows which areas can be provided with fire coverage, given that observer coverage is also available.
- For the location of a hypothetical observer in the terrain test area, a map showing points of which ground targets can be seen by the observer can be calculated and displayed. This map when overlayed on the previous map shows areas where fire support coverage is actually available.

The fire coverage problem above depends on the weapon and requires specific weapon launch and flight characteristics in addition to data about the terrain itself.

3. Accessibility

A common class of Marine Corps problems has to do with whether one point is accessible from another point along a specified path (e.g., a road) for a particular type of mobile equipment (e.g., a tactical mobile radar unit). Alternately, the accessibility problem could be whether any path between two points exists that a ground vehicle can traverse.

Many factors affect the answer to this problem including the type and size of the vehicle, the capabilities of the vehicle, the type and condition of the surface, and the slope of the surface. The slope of the surface is certainly one of the most important factors, and one type of solution is to map the areas showing points at which the maximum slope exceeds some limit. Such a mapping would provide a first-order order answer to the question whether one point is accessible from another.

4. Helicopter Safety Corridors

For helicopter operations it is important that the helicopter approach a target area as closely as possible without being detected or without being exposed for too long a period of time. If the exposure time can be minimized to the point at which an enemy sensor cannot track the helicopter well while the helicopter can detect and locate a target with

its own sensors, the helicopter, then, may be able to successfully launch a weapon and kill the target without being destroyed itself. The required helicopter exposure time would be minimized if "smart" weapons that can be launched without requiring a clear LOS between helicopter and target were employed.

Certainly, a critical element of such an operation will be the degree to which the helicopter can exploit the masking features of the terrain relative to the threat sensor. Computing and displaying masked/unmasked areas provides one means of identifying and selecting safe corridors for helicopters in a given region of operation.

5. Selected Test Problems

Based on the tactical problem areas that were considered and were briefly reviewed above, four types of basic problems of area mapping were identified. These are:

(1) Maps showing clear LOS paths from given observation points.

(2) Maps showing clutter relative to a given observation point.

(3) Maps showing fire coverage relative to a given weapon location point.

(4) Maps giving the slopes of given regions.

Problems (1) and (4) require primarily data about the terrain. Problem (2) requires additional information in the form of surface characteristics data and sensor characteristics. Problem (3) requires the specific characteristics about the weapon launch and flight and involves more complex algorithms to determine weapon trajectories as a function of range. We selected two of the above problems (1) and (4) as test problems for the evaluation. By limiting the number of test problems, we were able to examine more types of terrain and observation point locations. These test problems are restated here as:

- Test Problem I: Production of maps showing clear LOS paths for several observation points and regions.
- Test Problem II: Production of maps showing high slope areas for several regions.

B. Terrain, Observation Points, and Slope Thresholds

1. Terrain Regions

The selected terrain test area was a region near Twentynine Palms, California that provided a variety of terrain needed for evaluation. Figure 2 shows a section of a Defense Mapping Agency (DMA) contour map covering part of the Marine Corps Base at Twentynine Palms. The section shown in Figure 2 overlaps sheets entitled "Twentynine Palms West and Twentynine Palms East," and covers UTM coordinates 578000 E to 591000 E and 3797000 N to 3810000 N.

The digital data obtained from DMA consisted of a set of 9-track, 1600-bpi tapes, each covering an area of roughly 23-km easting and 28-km northing with a data grid spacing of 12.5 m. The tape containing the digital elevation data for the area shown in Figure 2 has the sheet name "29 PALMS-L." Its corners are shown in Figure 3. This data base (DB) was used to prepare a terrain data tape for use by SRI and SFU to generate the URG and TIN terrain models employed in the evaluation. It contains a window of 1024 points x 1024 points from the DMA DB covering an area of 12.8 km x 12.8 km or about one quarter of 29 PALMS-L. The relative location of this window is also shown in Figure 3, and the window corners in UTM coordinates are shown in Figure 4.

Although we initially anticipated fitting a TIN model to the entire 1024 x 1024 window, the TIN algorithms were not set up to process such a large window. A more manageable window size was determined to be 128 points x 128 points. Thus, the larger window was subdivided into 8 x 8 or 64 smaller windows, each covering an areas of 1600 m x 1600 m. Four of these smaller terrain regions were selected for the evaluation. The numbering convention for the subdivision is shown in Figure 5, and the four regions selected for evaluation were Regions 05, 06, 07, and 14. These regions are also shown in Figure 2.

Computer generated gray-scale images of each of the four test regions were prepared and displayed on the DeAnza TV image display system at SRI. Figure 6 shows the photographs that were taken of the TV images.

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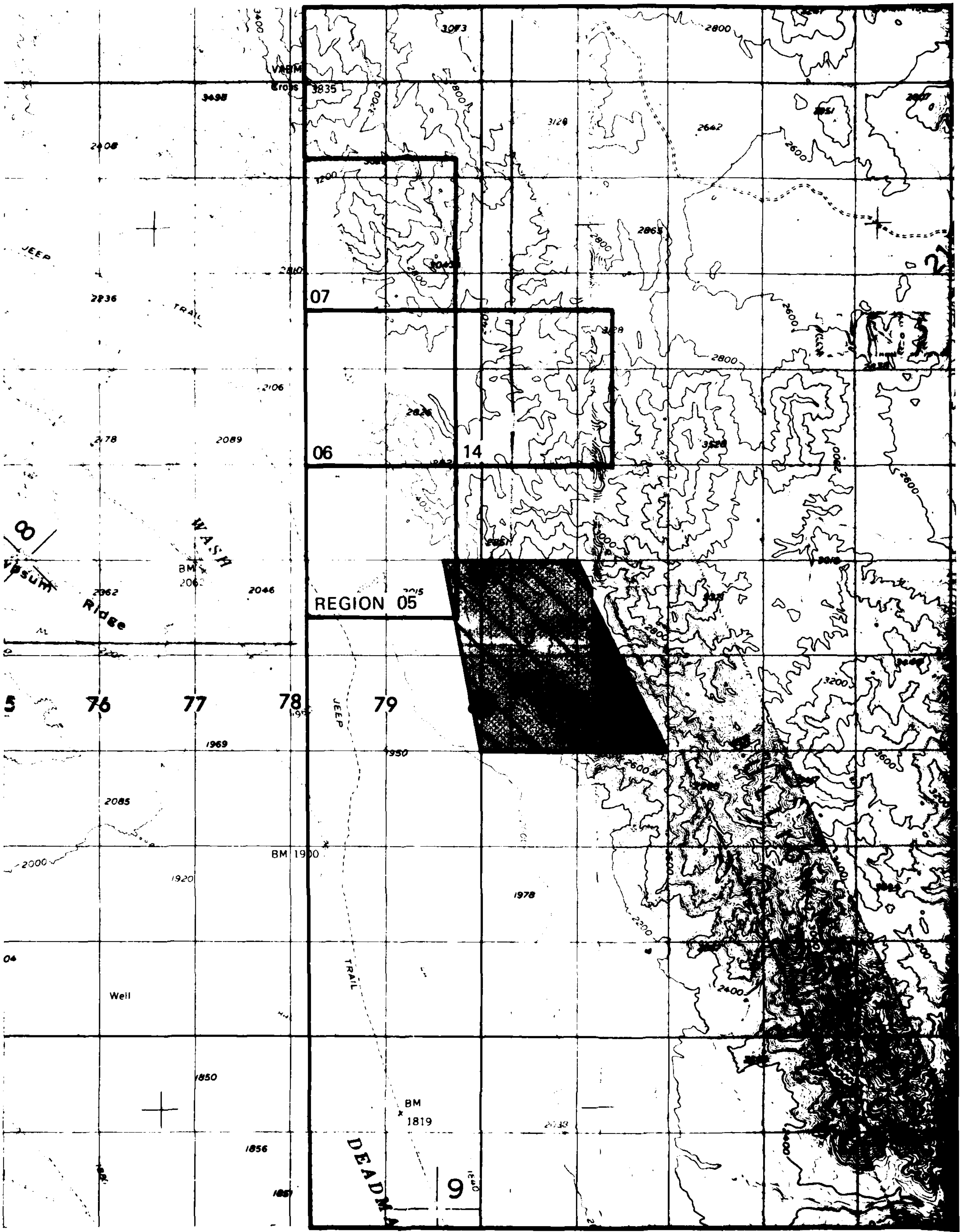
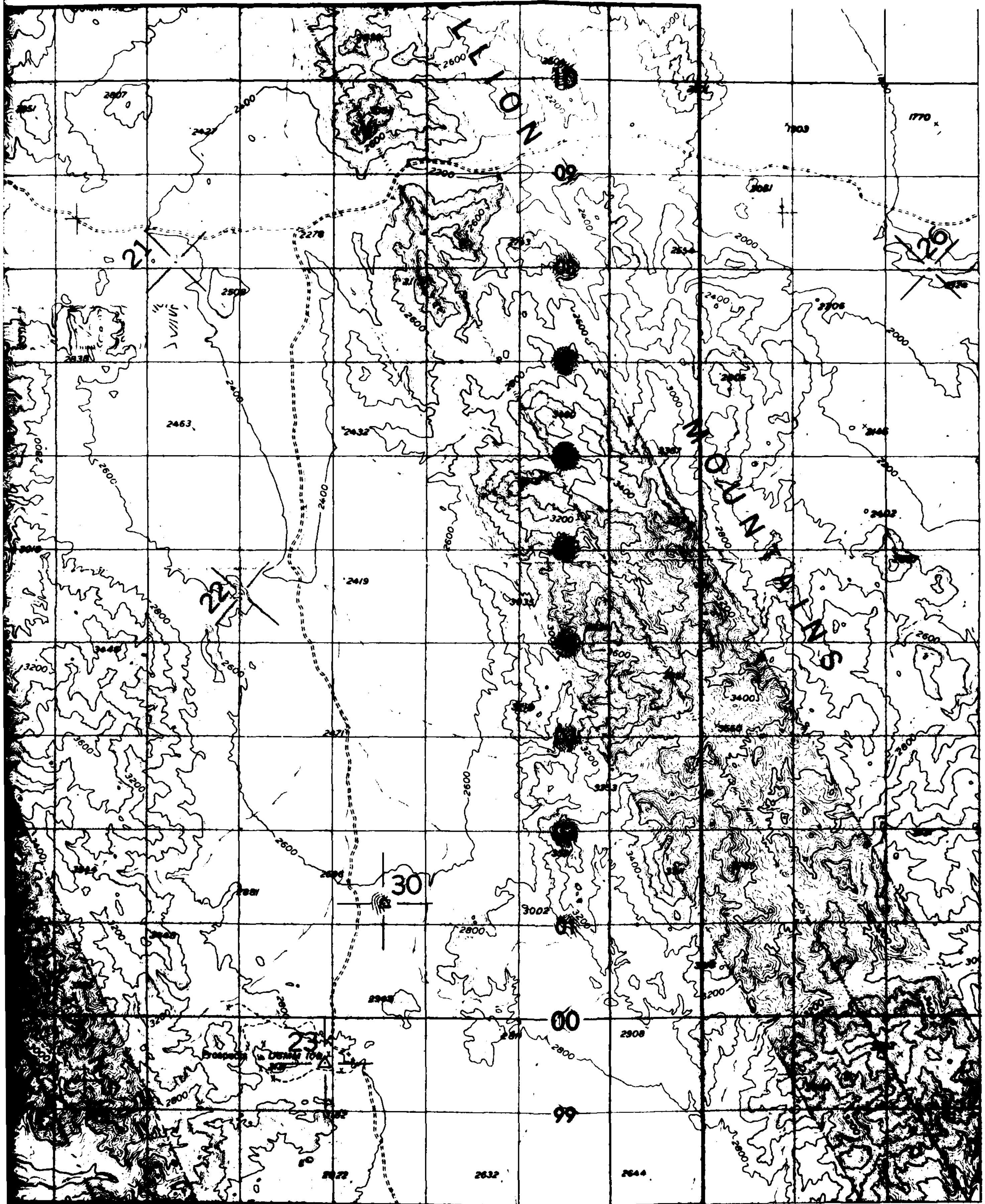


FIGURE 2 TWENTY-NINE PA



ENTY-NINE PALMS CONTOUR MAP

FIGURE 2

SHEET NAME: 29 PALMS-L

TAPE ID: 4366

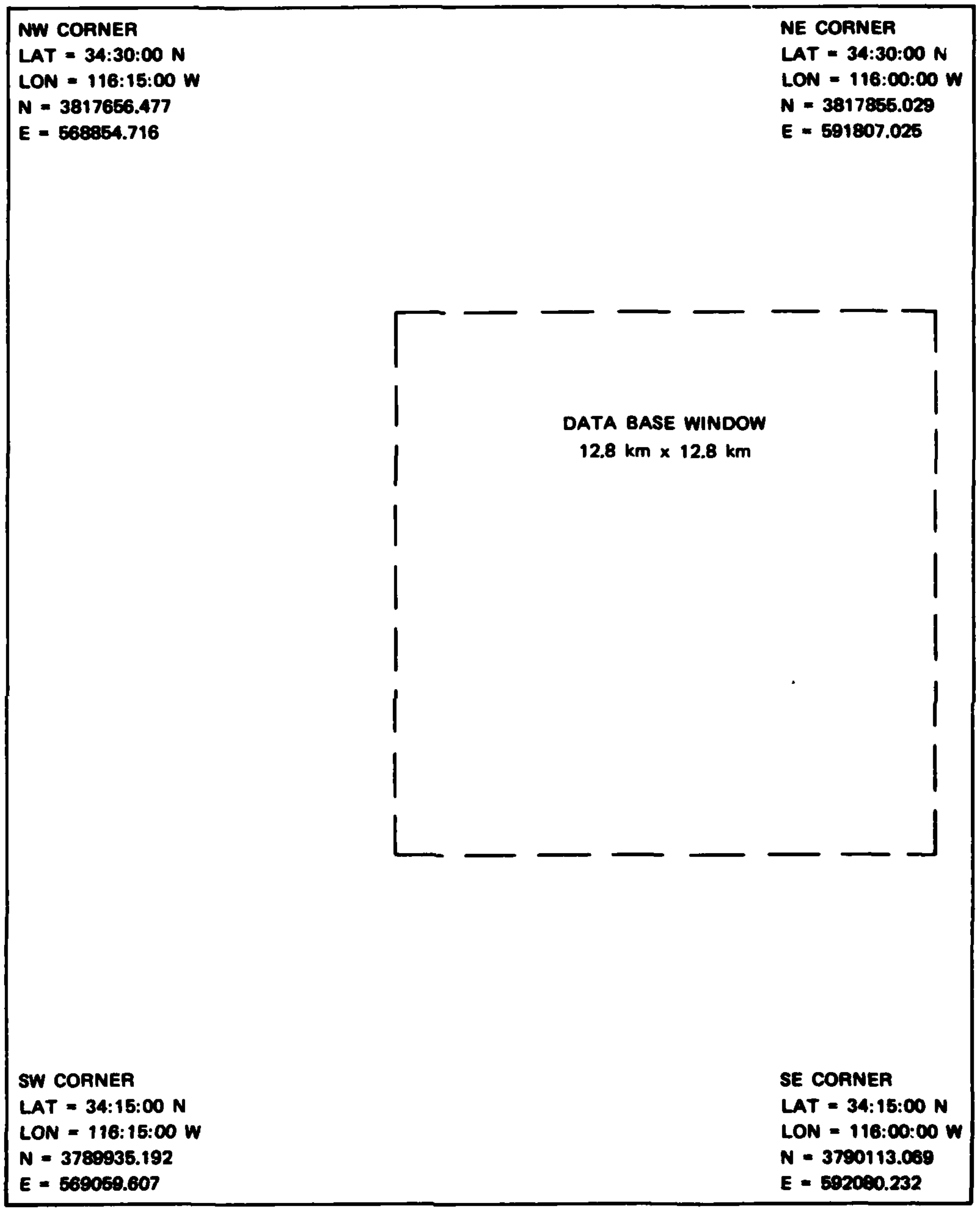


FIGURE 3 SHEET CORNERS OF 29 PALMS-L

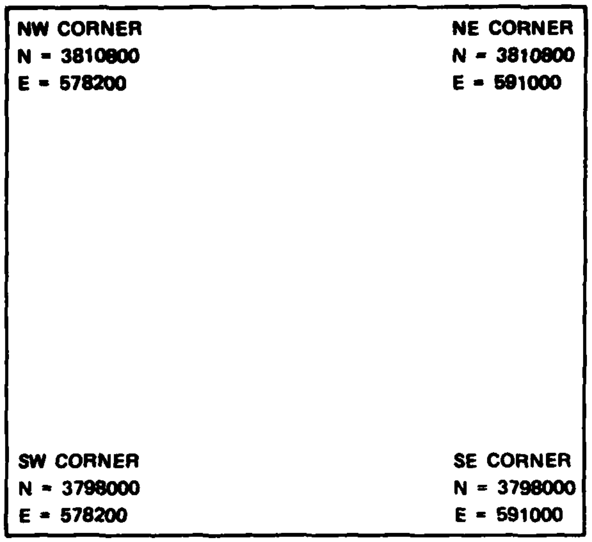


FIGURE 4 WINDOW CORNERS OF SELECTED TERRAIN AREA

08	16	24	32	40	48	56	64
07	15						
06	14						
05	13						
04	12						
03	11						
02	10						
01	09	17	25	33	41	49	57

FIGURE 5 NUMBERING CONVENTION FOR WINDOW SUBDIVISIONS

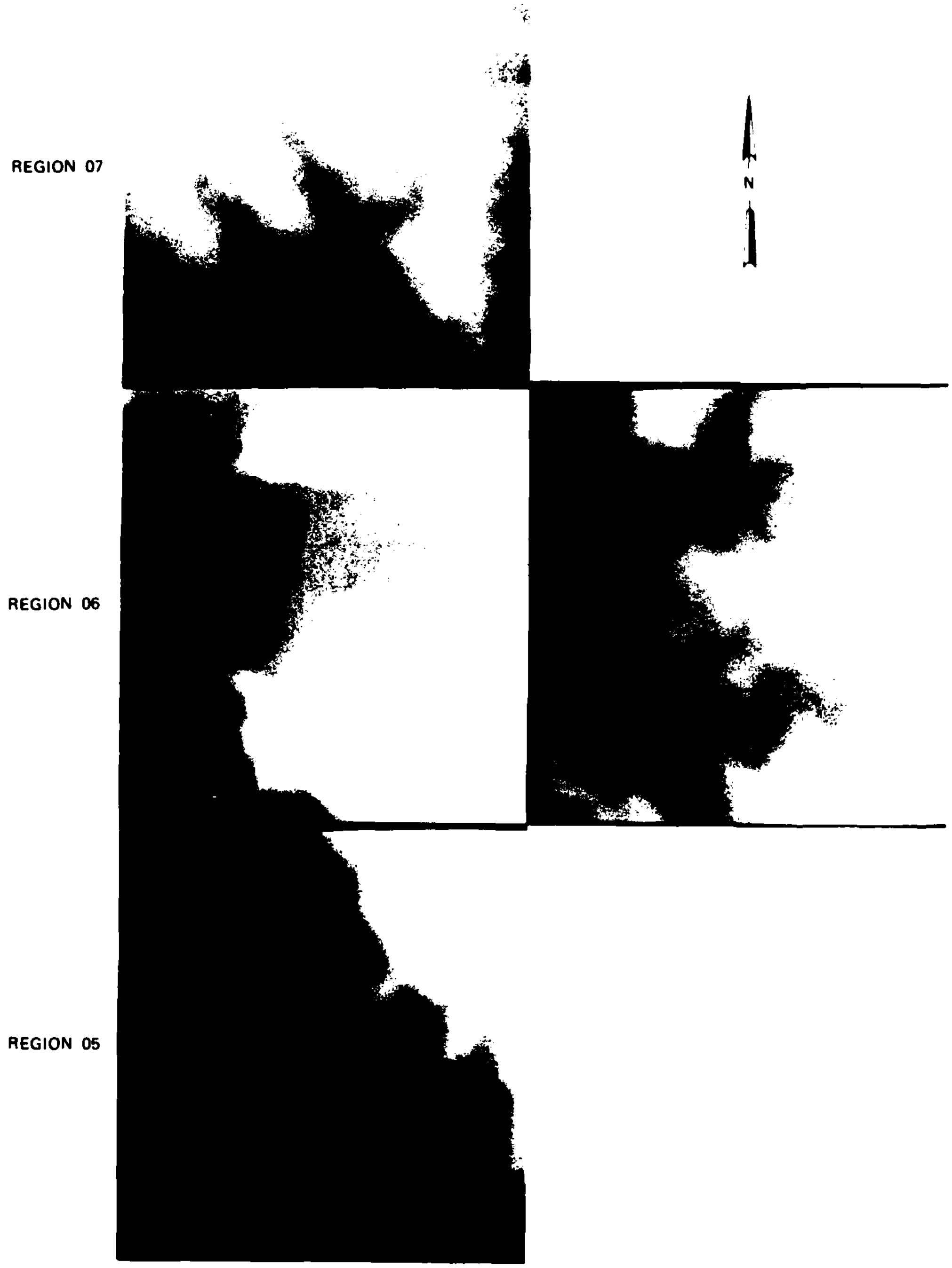


FIGURE 6 COMPUTER-GENERATED TERRAIN IMAGES

In these images bright or white areas correspond to higher elevations. Because of the combination of 8-bit quantization, and logarithmic scaling, which spreads out the gray scale at the ower elevations, the images show some contouring at the lower elevations. The gray levels for the four images were not registered with respect to each other, and thus, a certain degree of gray-scale discontinuity is seen between adjacent borders. Viewing the test regions in both the contour map (Figure 2) and gray-scale (Figure 6) reprseentations improves our mental image and understanding of the terrain features.

Region 05 is fairly flat over about 75 percent of the area. For example, in the northerly direction along the western edge, the terrain slope is only about 1.7 percent. In the northeast corner, hills rise about 600 ft above the plain.

Region 06, directly adjoining and north of Region 05 is fairly flat over about 50 percent of the area. Hilly areas lie to the southeast and northeast. The southeastern hills have two peaks of 2826 ft and 2821 ft elevation, respectively, and again rise about 600 ft above the plain.

Region 07, directly adjoining and north of Region 06 is hilly over about 80 percent of the region.

Region 14 is quite similar to Region 07.

The Twentynine Palms area and the four regions within that area were selected for the following reasons:

(1) it has a variety of terrain with a significant amount of relief.

(2) it has high points for the sensors.

(3) it has a significant variation in slopes for accessibility considerations

(4) it represents a challenging military operations area that is used for Marine Corps training.

2. Observation Points

Six observation points were selected within three of the four regions. These points are designated:

(1) 1C in Region 06

(2) 2N in Region 07

(3) 2S in Region 06

(4) 3C in Region 06

(5) 4N in Region 14

(6) 4S in Region 14

Table 1 gives the coordinates, elevations, and heights above the terrain for each of the observation points. The coordinates are given in absolute and relative UTM coordinates, where the relative coordinates are in reference to the southwestern corner of each terrain region. The heights of the observation points varied from 3.7 ft to 6.4 ft above the local terrain. The six observation point locations are also shown in Figure 7.

Table 1

OBSERVATION POINT PARAMETERS

Observation Point	Region	Coordinates: Northing UTM	Coordinates: Northing ΔUTM(m)	Coordinates: Easting UTM	Coordinates: Easting ΔUTM(m)	Terrain Elevation (ft)	Observer Height (ft)
1C	06	3806860.0	860.0	578440	240	2179.00	3.7
2N	07	3807601.0	1.0	578700	500	2266.60	6.4
2S	06	3807599.0	1599.0	578700	500	2265.92	3.7
3C	06	3806425.5	425.5	579225	1025	2825.36	3.7
4N	14	3806912.0	912.0	580551	751	2799.85	4.6
4C	14	3806876.0	876.0	580551	751	2799.87	4.6

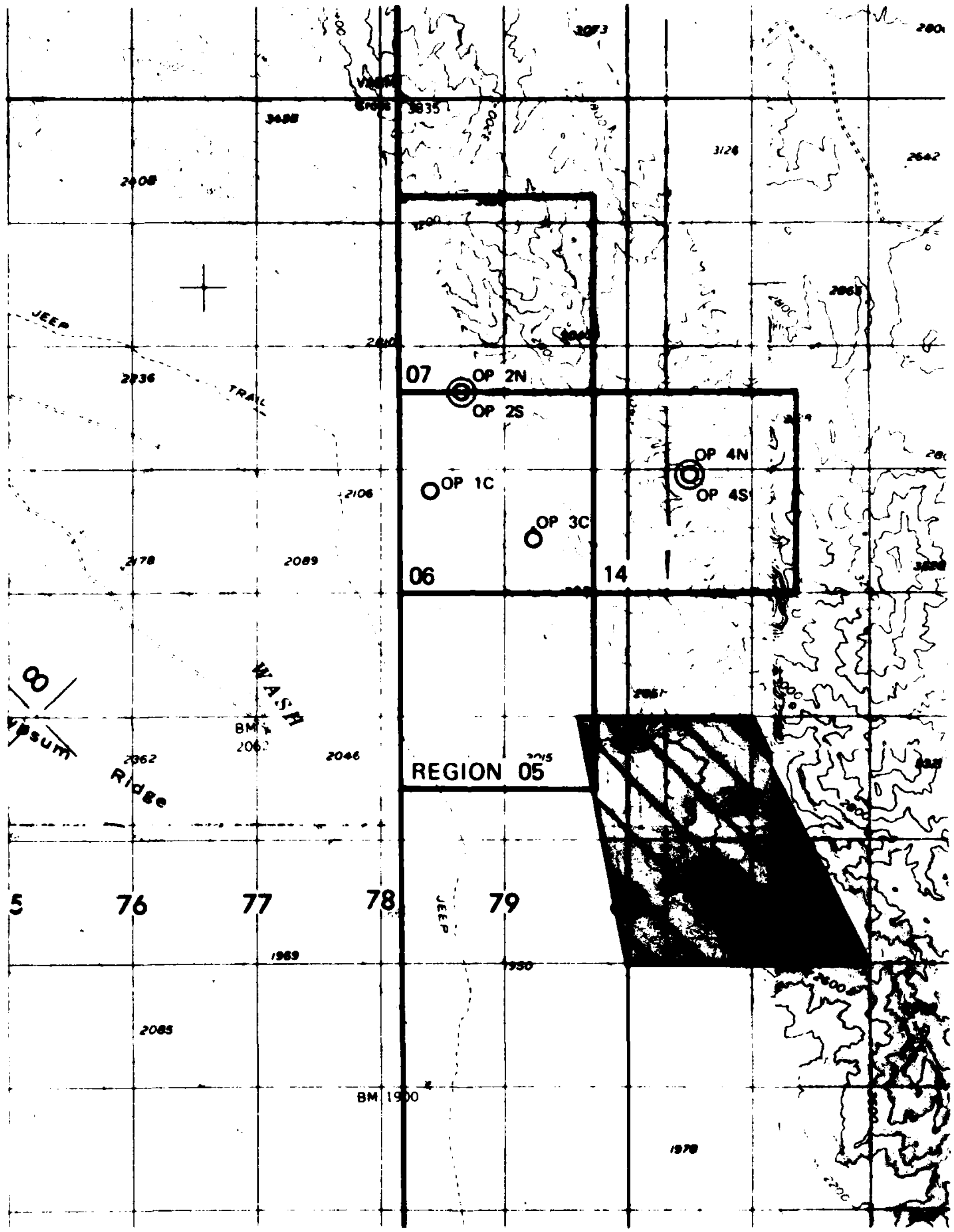


FIGURE 7 OBSERVATION POINT LOCATIONS

Observation Point 1C was selected in the plains areas of Region 06. Observation Points 2N and 2S are really one observation point in the foothills area on the boundary of Regions 06 and 07. From Observation Point 2N we consider northward LOSs into Region 07, and from Observation Point 2S we consider wouthward LOSs into Region 06. Observation Point 3C is on a peak in the hilly portion of Region 06. Observation Points 4N and 4S are on a small plateau within Region 14. Observation Point 4N is near the northern edge of the plateau, and Observation Point 4S is near the southern edge. These two points are 36 m apart in the northerly direction.

3. Slope Thresholds

Factors of terrain that affect cross-country movement, and therefore the accessibility of one point from another, are slope, soil composition, vegetation, man-made features, and drainage. Weather is also a very important factor; but unlike the others, it affects cross-country movement indirectly by influencing soil composition and drainage. Because this study did not investigate the interactions of all of these factors, we considered slope alone and derived slope maps that show the ground areas at which the maximum slope of the terrain exceeds selected thresholds.

Reasonable slope thresholds depend on the type of vehicle that must move over the terrain, e.g., tracked vehicles versus wheeled vehicle. Field Manual, FM 5-36, states that a 45-percent slope is commonly accepted as a reasonable upper bound for tanks, and a 30-percent slope for wheeled vehicles. These limits must be adjusted upoward or downward depending on prevailing weather conditions and other terrain factors. For the purpose of this comparative evaluation, the 30 percent and 45 percent slope thresholds were used for generating slope maps for each of the selected terrain regions.

IV GENERATION OF TIN AND URG DATA BASES

In the initial plan for the evaluation, SRI was to provide SFU with data tapes of the Twentynine Palms area, and SFU would calculate the TIN for selected areas. They would send the tapes containing the resulting data and their software routines for generating visibility maps and slope maps from the TIN data to SRI. SRI would convert the software routines to run on the KL-10 system (at SRI) and the remaining portion of the evaluation involving solution of the test problem using both TIN and URG DBs would be done on the KL-10.

The first part of this plan was carried out by the SFU team who provided SRI with tapes of the TIN data for Twentynine Palms. The second portion of the plan required the conversion of SFU software from the IBM PL/I language to SAIL or FORTRAN for the KL-10. Rather than undertake such a conversion, we decided that the process could be handled more efficiently if the SFU personnel came to SRI and ran their programs using the IBM 370 series computer at Optimum Systems Incorporated (OSI) in Santa Clara. The SRI software routines for generating visibility and slope maps were, then, written in FORTRAN, run, and debugged on the KL-10. Then the debugged programs also were run on the IBM 370 at OSI to compare the computer resource measures.

A. TIN Model Generation

The TIN construction process transforms the input elevation grid into a triangulated irregular network in two phases. In the first phase, points of structural importance are selected from the grid model and are connected into an initial triangulation. The second phase compares the triangulated model with the grid and introduces additional "support points" to reduce the maximum error below a specified tolerance. Each support point divides the triangular facet in which it occurs into three new trinagles creating a new triangulation. These new triangles are

added to the list of triangles to be considered for possible additional support points. When the list is exhausted, the TIN process is complete. Note that once a point is added to the triangulation, it never is deleted. This insures that the original set of structural points are always retained, a desirable property.

The original set of structural points are selected to define important surface-specific points and lines, including the points that define the boundary lines of the region being "TINed." The boundary points are included in any TINed region sharing common boundaries. Boundary line points are selected to include endpoints of boundary curves, local maxima and minima in elevation, and other points to fit the boundary curvature to some defined tolerance. Within the interior of the region, points are selected that define the important ridges, channels, peak and pits. These structural points are then connected into a triangulation using the Delaunay Triangulation Procedure[*].

The above is a very brief conceptual description of the TINing process. The actual TINing process employed in this study is a fully automated procedure operating on high-resolution input elevation data defined on a uniform grid.[†]

The URG data tape sent to SFU consisted of a grid of 1024 points x 1024 points, previously described in Figures 4 and 5. Because the western portion of the window appeared representative of the entire window, we TINed only one-fourth of the 1024 x 1024 window consisting of Regions 01 through 16 as defined in Figure 5. Each of these 16 regions were TINed separately from a grid of 129 points x 129 points grids. Although each region is defined by a nonoverlapping grid of 128 points x 128 points, it was necessary to use grids of 129 points x 129 points that overlap at the boundaries between adjacent regions to provide continuity at these

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[*] R.J. Fowler, "DELTRI: An Efficient Program for Producing Delauney Triangulations," Technical Report 18, ONR Contract #N00014-75-C-0886, Simon Fraser University, Burnaby, B.C., Canada (1977)

[†] R.J. Fowler and J.J. Little, "Automatic Extraction of Irregular Network Digital Terrain Models," Proceedings of SIGGRAPH '79, Chicago, Illinois , (1979).

boundaries. Regions 08 and 16 are exceptions since they require overlapping boundaries only at the eastern borders. These two regions were TINed using grids of 128 points x 129 points.

Regions 05, 06, 07, and 14 are four neighboring regions that comprise the terrain data used in the evaluation. Figure 8 shows the TIN points overlayed on the TV gray-scale images that were originally shown in Figure 6. The triangle edges connecting the points are not displayed since software for generating these borders from the digital data was not available. Figure 8 does, however, show the points required for each region, and the distribution of these points. Table 2 gives pertinent TIN data and statistics. The number of points required ranges from 639 points to 2886 points. As expected, the minimum number is required for Region 05, and the next greater number is required for Region 06. Since Regions 07 and 14 have greater frequency of elevation variation, these require significantly more TIN points.

Table 2

TIN STATISTICS

Region TINed	Number of Points Required	Elevation Spread (ft)	Average Elevation Difference (ft)	RMS Difference (ft)	Maximum Difference (ft)
05	639	780	1.86	14.2	49
06	1282	734	2.61	22.3	51
07	2286	1300	4.50	55.0	67
14	2886	920	3.50	51.0	207

Table 2 also lists the average, rms, and maximum elevation differences between the TIN model and the URG high resolution model. Because we assume that the high-resolution data serves as the baseline, these differences can be considered errors introduced by the TIN modeling process. Unfortunately, at the present time there is no rapid method

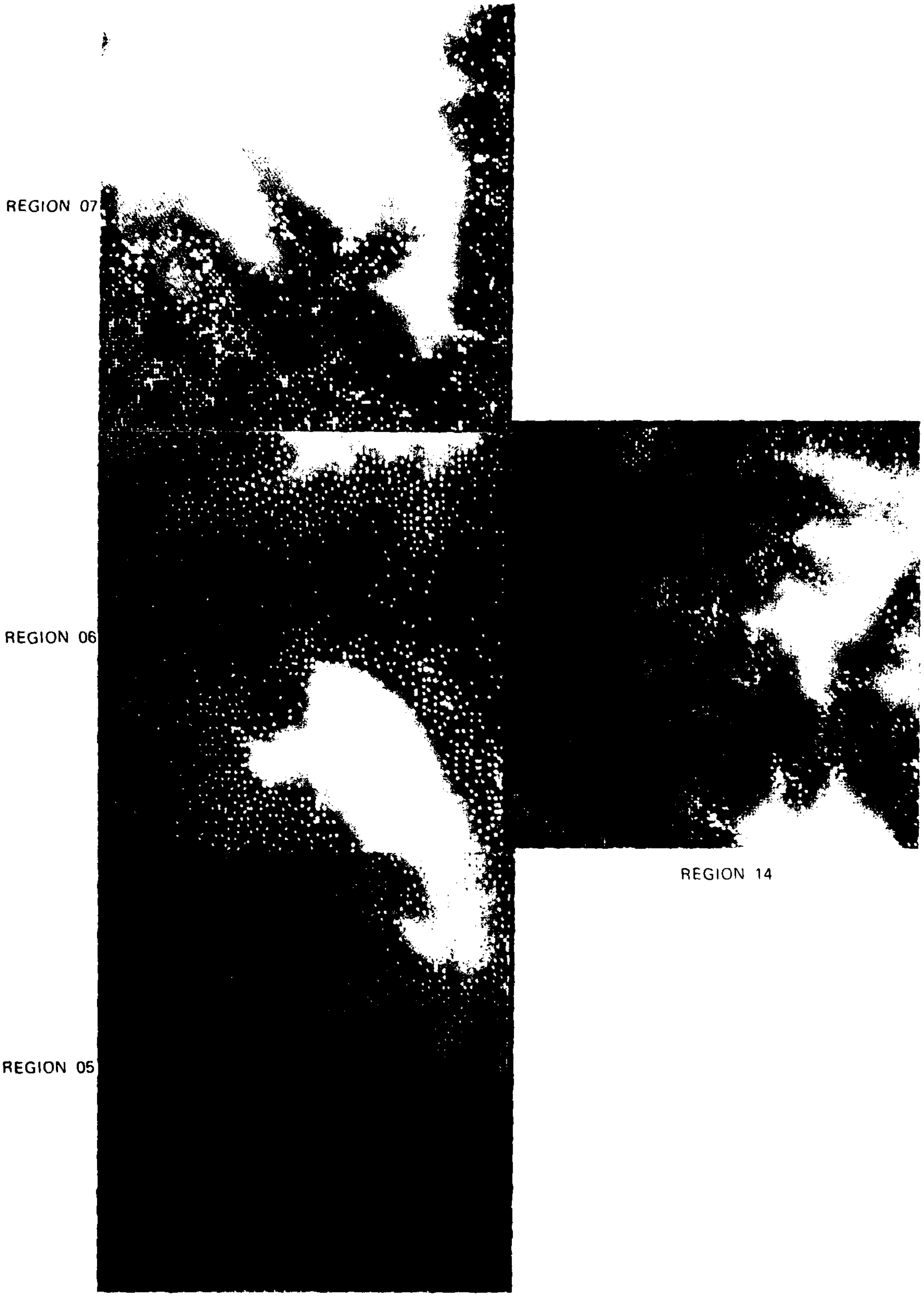

FIGURE 8 TIN POINTS

of optimizing the TINing process. These error values were obtained after a reasonable effort was expended to TIN the terrain data. Ideally, we would like to minimize one of the error measures for a given number of TIN points, or minimize the number of TIN points for a given error measure value.

B. URG Model Generation

A sequence of URG models for each of the regions used in the evaluation were generated by the simple processs of deleting points from the high resolution DB to generate lower resolution DBs. The relative resolution factor, R, is defined as the factor by which the number of rows and columns is reduced in the DB. Thus, for each value of R, every Rth point is retained. In addition to the high resolution URG model (R=1), URG models for R equal to 2,4, and 8 were generated.

Difference or error statistics were not generated for these URG models. However, the maximum elevation error that can occur is equal to the maximum change in elevation between adjacent (including diagonals) grid points times 0.5R.

C. Data Base Storage Requirements

Encoding the TIN data requires the following for each TIN point:

(1) X coordinate

(2) Y coordinate

(3) Z elevation

(4) n number of neighbors

(5) p pointer to neighbors list

(6) p_1 pointer to neighbor 1

.

.

.

(5 + n) p_n pointer to neighbor n.

The average value of neighbors, n, for the regions TINed was about 6. Thus, 11 words are required to encode each TIN point. We can compute and compare the number of bytes (8 bits each) required for both the TIN and URG DBs with a few assumptions. One byte each will be required for X and Y, and if we desire a one foot elevation accuracy, at least two bytes will be required for z. The number of neighbors, n, will require only one byte. Finally, each of the pointers will require two bytes. Thus, if N is the number of TIN points, 19 bytes will be required for each of these points, and 19 x N bytes will be required for the DB.

For the URG DB, we need only encode the elevations with 2 bytes each. If R is the relative resolution, then $(2 \times 128^2)/R^2$ is the number of bytes required per URG DB. Table 3 gives the number of bytes required for each of the URG and TIN models. We see that TIN requires greater storage for Regions 07 and 14 than even the highest resolution URG models. On the other hand, TIN requires less storage than the highest resolution URG for Regions 05 and 06, but more storage than any of the lower resolution URGs. In effect, from storage considerations, the TIN DB for Region 05 is comparable to an URG DB at a relative resolution of 1.64, and the TIN DB for Region 06 is comparable to an URG DB at a relative resolution of 1.16.

Table 3

DATA BASE STORAGE REQUIREMENTS

Region	URG Data Bases (Number of Bytes)				TIN Data Base (Number of Bytes)
	R = 1	R = 2	R = 4	R = 8	
05	32768	8192	2048	512	12141
06	32768	8192	2048	512	24358
07	32768	8192	2048	512	43434
14	32768	8192	2048	512	54834

V TEST PROBLEM ALGORITHMS

Two test problem algorithms for each of the two types of DBs were written for the evaluation. One algorithm generates visibility maps, while the other generates the slope maps.

A. Visibility Algorithms

A visibility map is a plan map of the terrain model showing the areas visible from a given observation point within a digital terrain model. It consists of a set of rays emanating from the observation point, and along each ray, the visible terrain is indicated by filling in the ray. Where a portion of terrain along the ray is not visible from the viewpoint, the ray is interrupted. Because the determination of visibility is made only along each ray, which is a path of zero width, the representation of visible areas is limited by the density of the rays, which, in turn, is controlled by specifying their angular separation.

1. TIN Visibility Algorithm

Generating visibility maps from the TIN DB is performed by an algorithm, called VISIB, and proceeds as follows: Given the coordinates of the observation point, VISIB determines in which triangular facet the point lies, and calculates the height of the surface at that position. VISIB then constructs the set of rays emanating from that point, separated by a specified angle, starting from 0° to some final angle. On each ray, the program builds a profile of the surface height, essentially a vertical slice through the surface along the direction of the ray. Since the TIN is composed of planar triangular facets, the profile is composed of straight line segments. Starting at the origin of the ray, the angle of a vector from the observation point to the endpoint of the current segment is calculated, and this angle is compared with the current maximum elevation angle. At the start the elevation angle is set to -90°. If the angle to the endpoint

of the segment is higher than the previous maximum, the point is visible. If both endpoints of a segment are visible, the entire segment is visible, and the portion of the ray that represents this segment is encoded and saved. If the near endpoint of a segment is invisible, and the far endpoint visible, only a portion of the segment is visible. When this occurs, the intersection of the current maximum angle with the segment is found, and the portion of the segment from that point to the far endpoint is encoded and saved. When the far endpoint is visible, the maximum angle is given the new value. VISIB continues in this fashion, until the profile is finished.

A profile of the surface height at a given azimuth consists of a list of distances from observation point to the endpoints of the linear segment and the corresponding elevation of these endpoints. The triangle within which the observation point lies and then the point at which the ray emerges from the triangle must be found. This point is the first point along the profile. Next, the triangle being entered by the ray is determined. This is either a triangle that shares a common vertex only, or two vertices and a side. The emergence point from the new triangle is computed to give the next point along the profile. This process is repeated until the ray reaches the boundary in the TIN DB.

2. URG Visibility Algorithm

The URG visibility algorithm, called VISMAP, does not select rays at equal angular intervals; rather, after each ray has been processed, the next angular increment is determined by the next point on the boundary a distance of one intergrid spacing away. The angular increment is then determined by the angle subtended by the boundary segment relative to the observation point. Starting from the observation point, points are selected sequentially along the ray so that they are separated by the intergrid spacing distance. The elevation of the point is determined by a bilinear interpolation of the URG data. The angle of the vector from the observation point to the current point is calculated; this angle is compared with the current maximum elevation angle. If the angle is greater than or equal to the current maximum

elevation angle, the point is visible. If the previous point was also visible, the current segment is visible, otherwise only a portion is visible. The visibile portion is determined by the intersection of the current maximum elevation angle with the segment. After the visible portion of a given segment is determined, the elevation angle of the current point becomes the maximum elevation angle. If the current point is not visible, the entire segment is not visible.

B. Slope Map Algorithms

A slope map is a plan map of the terrain model that shows the maximum slope of the terrain at each point in a rectangular grid of points. Quantization and thresholding of the slope values are used to provide the discrete ranges of slope values. A binary slope map is a slope map in which a single slope threshold is employed to determine whether the maximum slope at a point is above or below the threshold. The same thresholding process for both the TIN and URG DBs is used to produce a binary slope map from any given nonbinary slope map. We will discuss only the generation of the nonbinary slope map.

1. TIN Slope Algorithm

With the TIN DB, generating a slope map on a grid of points involves first determining in which triangle each of the points lie, and then, the maximum slope of the triangle. The algorithm for generating slopes from the TIN DB is called SLOPER. SLOPER determines the maximum slope of the triangle by computing the angle between the zenith and the normal to the triangular facet. Since many of the grid points selected will lie within the same triangle, and the maximum slope calculation is identical for each of these points, the TIN DB (a node structure) is first converted to its dual structure (a triangle structure). For each triangle, the maximum slope is computed only once and saved.

2. URG Slope Algorithm

Maximum slopes for the URG DBs are determined on a grid of points corresponding to the URG data grid. For each point in the grid, a

small triangular facet is formed by the point and its two neighbors in the north and east direction. The maximum slope of that triangular facet is considered the maximum slope of the terrain at that point. The slope maps are constructed on a grid corresponding to the dense high-resolution grid by assuming that the slopes are constant at the points originally deleted. Their values are set equal to the values computed for the southwesternmost cornerpoints of the low-resolution cells.

C. Error Measure Algorithms

The error measure employed in the evaluation was the difference in area between the binary visibility and the slope maps generated from the high-resolution URG DB, and the corresponding maps generated from the TIN DB and each of the lower-resolution URG DBs. Of course, two types of differences, corresponding to the two types of possible errors, exist.

The slope map difference algorithm is very straightforward. For each point in the grids of the two binary slope maps, the algorithm simply determines whether the maps agree or not. For each of the two possible ways they can disagree, the number of points of disagreement are simply summed. The ratio of this sum to the total number of grid points times 100 is the error in percent of total region area.

Areal differentiation in the visibility map is somewhat more complex because the map is described in terms of vectors of zero thickness. Thus, the boundaries of the visible areas are not directly available. The approach employed considers the vectors to have a linearly varying thickness defined by the angular width of the spacing between vectors in the azimuthal direction. Essentially, these vectors define very thin pie-shaped slices of the visible area. The length of the visible vectors and the radial distance of their endpoints define the areal portion of the pie-shaped slices that are visible.

This approach requires that the two visibility maps being compared have the same angular increment between vectors. Because the URG visibility maps were determined with irregular angular increments, they

must be transformed to equal angular increment mappings. This is done by first determining in what way the vectors should be connected to form the boundary of the visible area, and then interpolating between the neighboring vectors to obtain the new endpoints of vectors at the desired azimuthal spacing. Determining the boundary relations involves checking each vector against its neighbors to identify where the radial distances between the vector endpoints overlap. After identification of all of the overlapping neighboring vectors, the distances between endpoints are used to decide which ones should be connected.

Once a pair of visibility maps have been registered with respect to the angular distribution of rays, the area differences are calculated as the sum of all the pie-shaped segments corresponding to non-overlapping portions of the visibility vectors.

VI TEST PROBLEM RESULTS

A total of 40 slope map and 30 visibility map cases were evaluated. The 40 slope map cases were generated by 4 terrain regions, 5 DBs (1 TIN and 4 URGs), and 2 slope thresholds. The 30 visibility map cases consisted of 6 observation points for 5 DBs. The slope map cases are identified by listing in sequence the type of DB, the region, the resolution factor (R), where appropriate, and the slope threshold. Thus, for example, URG06-R4-S45 corresponds to the URG DB for Region 06 at resolution factor of 4 and with slope threshold of 45 percent. TIN06-S45 is the corresponding case for the TIN DB. The visibility map cases will be identified by listing in sequence the type of DB, the observation point, and the resolution factor (where appropriate). Thus, URG2N-R1 is the baseline DB case (since R = 1) for observation point 2N.

A. Visibility and Slope Map Image Displays

A selection of slope maps and visibility maps were displayed on the DeAnza digital image display system and then photographed for this report. These photographs illustrate one form of output for the solutions of the test problems. In each case, the visibility map or slope map is overlayed on the gray-scale image of the terrain of the region. For the lower-resolution cases, corresponding lower-resolution gray-scale images were used as background. However, in the TIN DB cases, the maps are overlayed on the baseline DB image. We did this because we did not have the necessary software to convert the TIN DB into gray-scale images.

Figures 9 through 14 show the TIN and baseline URG visibility maps for each of the six observation points. Figure 9, for example, shows the visibility maps for Observation Point 1C (e.g., for cases URG1C-R1 and TIN1C). The displays show the rays at a spacing of 5° although the digital computation of the difference in visible areas between

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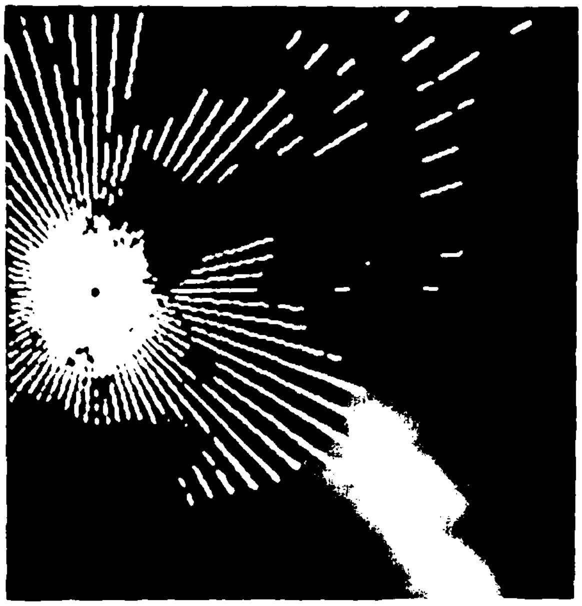
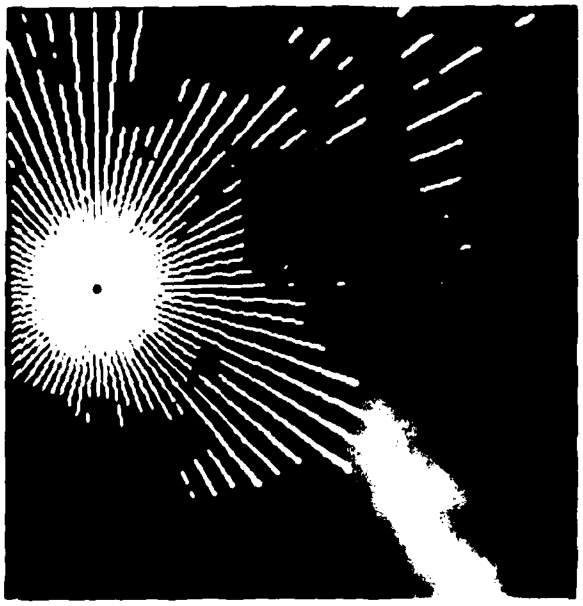
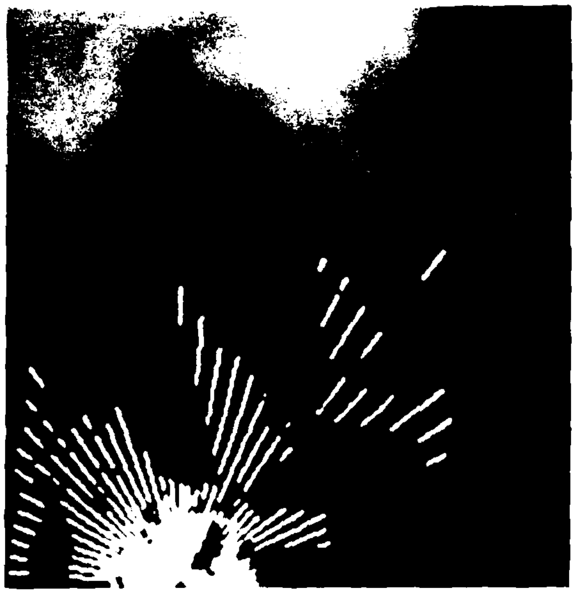


(a) URG1C-R1



(b) TIN1C

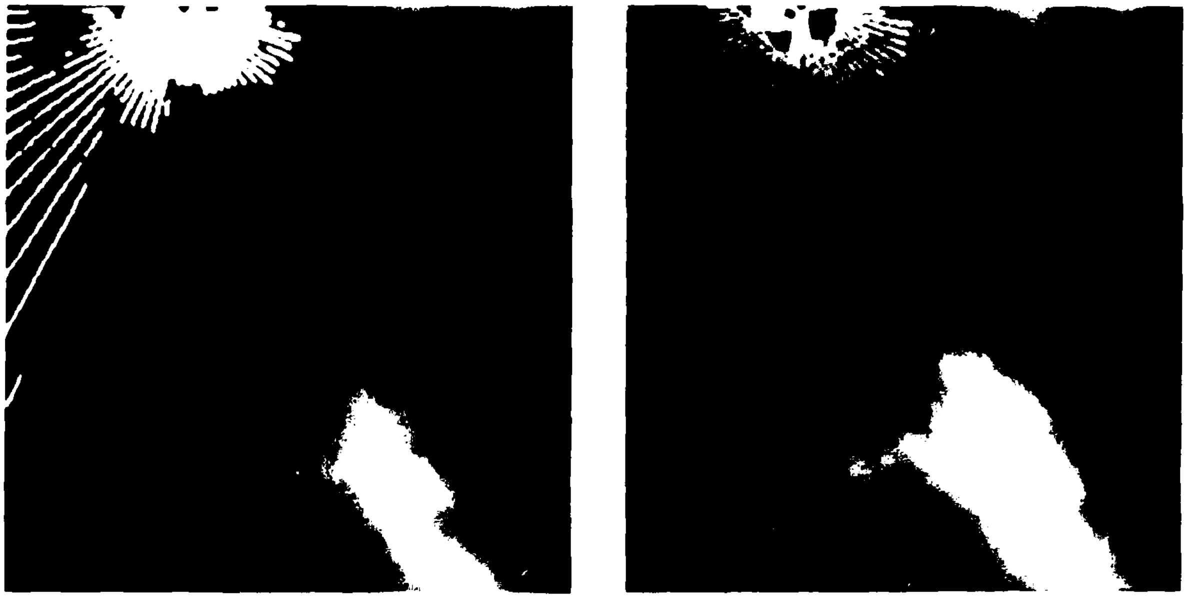
FIGURE 9 VISIBILITY MAPS--OBSERVATION POINT 1C



(a) URG2N-R1

(b) TIN2N

FIGURE 10 VISIBILITY MAPS--OBSERVATION POINT 2N



(a) URG2S-R1 (b) TIN2S

FIGURE 11 VISIBILITY MAPS--OBSERVATION POINT 2S

(a) URG3C-R1 (b) TIN3C

FIGURE 12 VISIBILITY MAPS--OBSERVATION POINT 3C

(a) URG4N-R1

(b) TIN4N

FIGURE 13 VISIBILITY MAPS--OBSERVATION POINT 4N

(a) URG4S-R1

(b) TIN4S

FIGURE 14 VISIBILITY MAPS--OBSERVATION POINT 4S

visibility maps used vectors spaced one degree apart. The display spacing of 5° prevents excessive running together of the rays at radial distances near the observation point.

These displays allow visual comparisons of the effects of the baseline terrain data and the other TIN and URG DBs. For Observation Point 1C, we see that in the southeast and northeast direction visibility is blocked by the hilly terrain. Closer in, in the northeast direction, the terrain slopes gently upward, initially at a greater slope, then at a reduced slope. The observation point then appears to be in a shallow depression, and thus, the flatter terrain is not visible. Interestingly, the TIN case does not show this effect. Apparently, the LOS at the local horizon makes a small grazing angle with the flatter nonvisible terrain, and the TIN triangulation smooths out the terrain sufficiently to eliminate the closer, local horizon.

Eventually, the terrain to the northeast begins to rise more rapidly and becomes visible again. A similar situation occurs in the southerly direction except that the terrain continues to stay fairly flat past the local horizon.

Observation Point 2N is located near the southern border of the very hilly Region 07. The terrain is thus fairly severely blocked over most of the region. Observation Point 2S is essentially the same as Observation Point 2N, but located on the northern border of Region 06. Except for the southwesterly direction, most of the terrain is severely blocked by the hills just to the south of the observation point.

Observation Point 3C is on a peak in the southern half of Region 06. For the observation height of 3.7 ft, the rapid fall-off of the terrain near in blocks the downslopes, as well as a fairly large portion of the plain below. However, most of the terrain further out toward the borders of the region is visible. A higher observation point would have allowed more of the plain to be visible.

Observation Points 4N and 4S are both in Region 14, separated by 36 m, and on opposite edges of a small local plateau. As expected,

visibility from Observation Point 4N is mostly blocked to the south, while visibility from Observation Point 4S is mostly blocked to the north.

Visibility maps for Observation Point 1C for each of the five DB are shown in Figure 15. The first four images are for the different resolution URG DBs. The resolution can be seen in the background gray-scale image of the terrain. Comparing the sequence of URG cases, we see the smoothing effect of the lower resolution data. The nonvisible area in Figure 15(a), to the northeast of the observation point and centered about one quarter of the radial distance outward, first begins to close up and then shrinks as lower-resolution data is used. In overall shape, size, and area features, the TIN case appears to be closest to the lowest-resolution case (R = 8).

Figures 16 through 19 show the 45-percent threshold slope maps for the baseline URG and TIN DB cases. These binary maps are overlayed on the gray-scale images of the terrain. The whitest or brightest regions correspond to areas where the slope exceeds the specified threshold. A visual comparison of these slope maps indicates fairly good agreement between the baseline URG and TIN DB cases.

Slope maps for Region 06 for each of the five DB are shown in Figure 20. Recall that the slope map consists only of the brightest or whitest cells; other lower intensity cells correspond to the gray-scale background terrain image. The first four images are for the URG DBs, and the last is for the TIN DB. The TIN slope map falls somewhere between the baseline URG and the R = 2 URG DB in visual comparison.

B. Error Measures

Visibility and slope errors are obtained by determining the amount of area where the various DB results differ from the baseline DB results. There are two types of areal differences that can occur. In the case of the visibility map, an area may be truly maksed or non-visible, but may be shown as unmasked or visible: a Type I error. The opposite case results in a Type II error and occurs when a truly unmasked

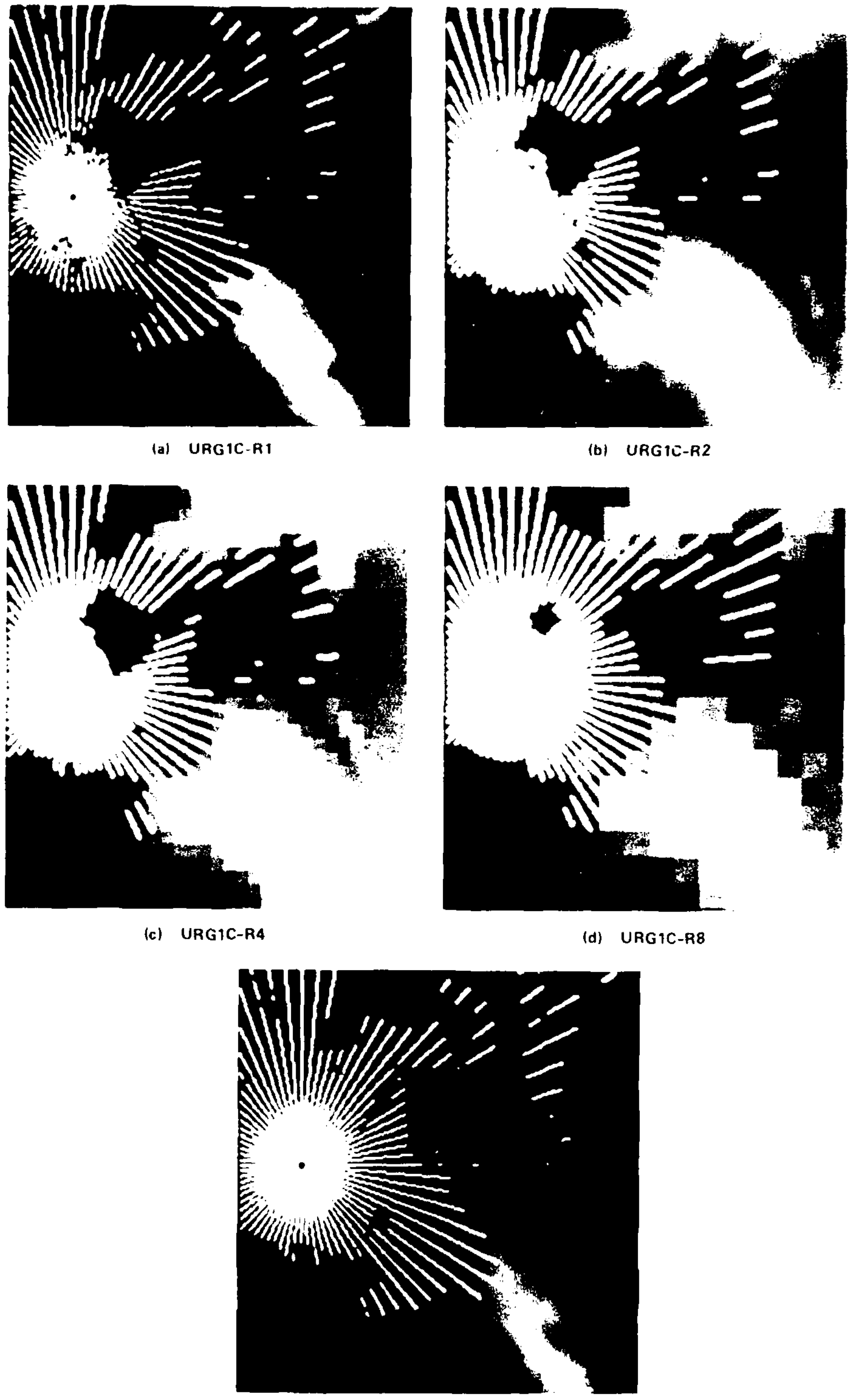
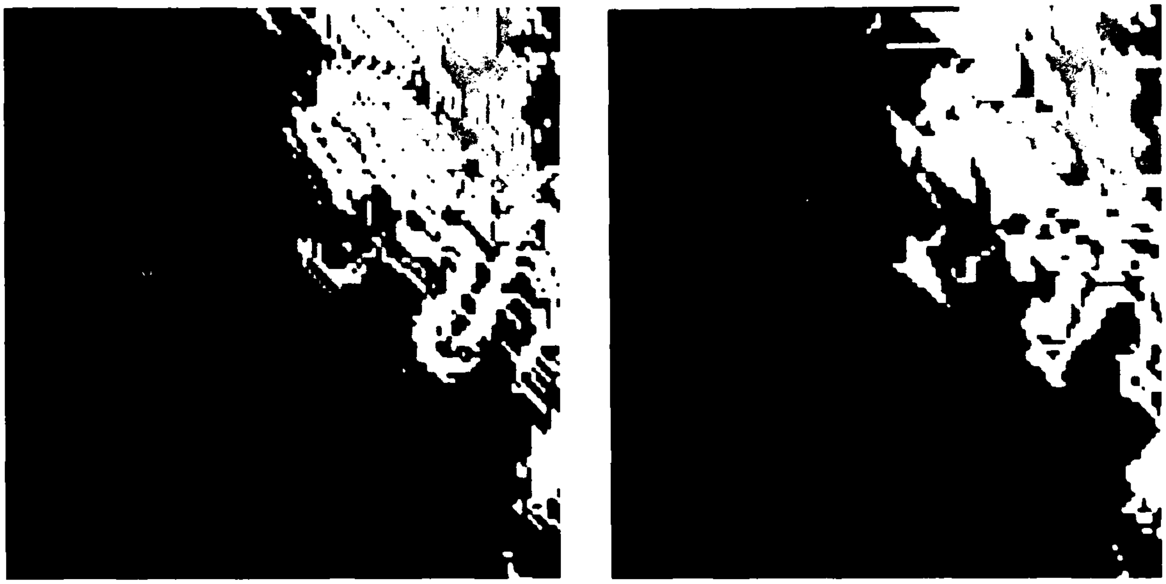
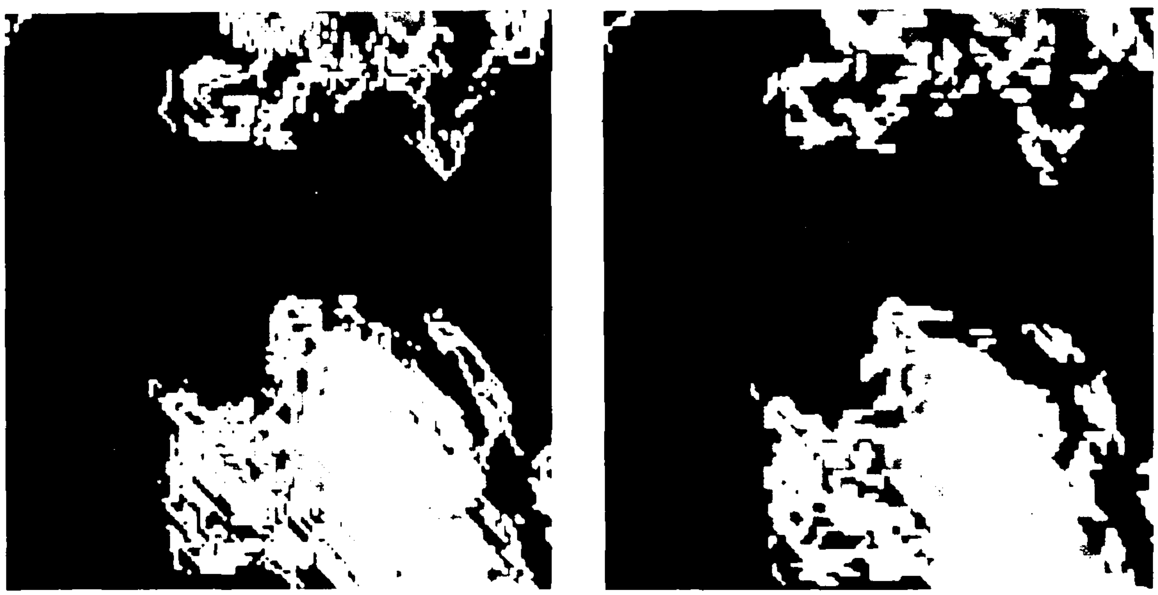


FIGURE 15 VISIBILITY MAPS--POINT 1C - TIN AND URG DBs



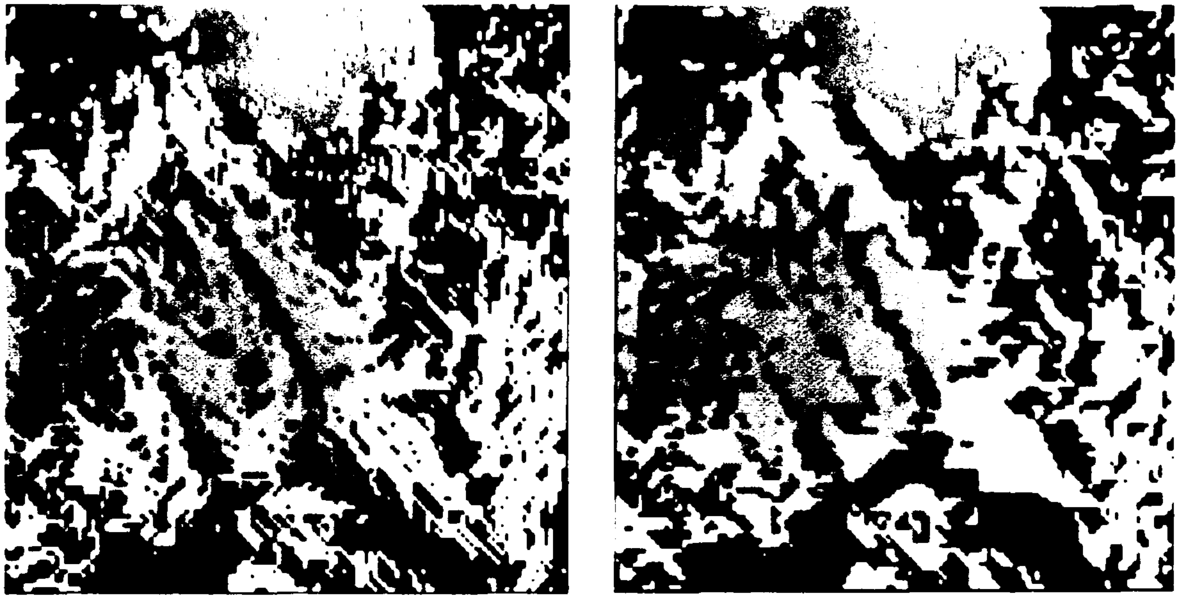
(a) URG05-R1-S45 (b) TIN05-S45

FIGURE 16 SLOPE MAPS--REGION 05



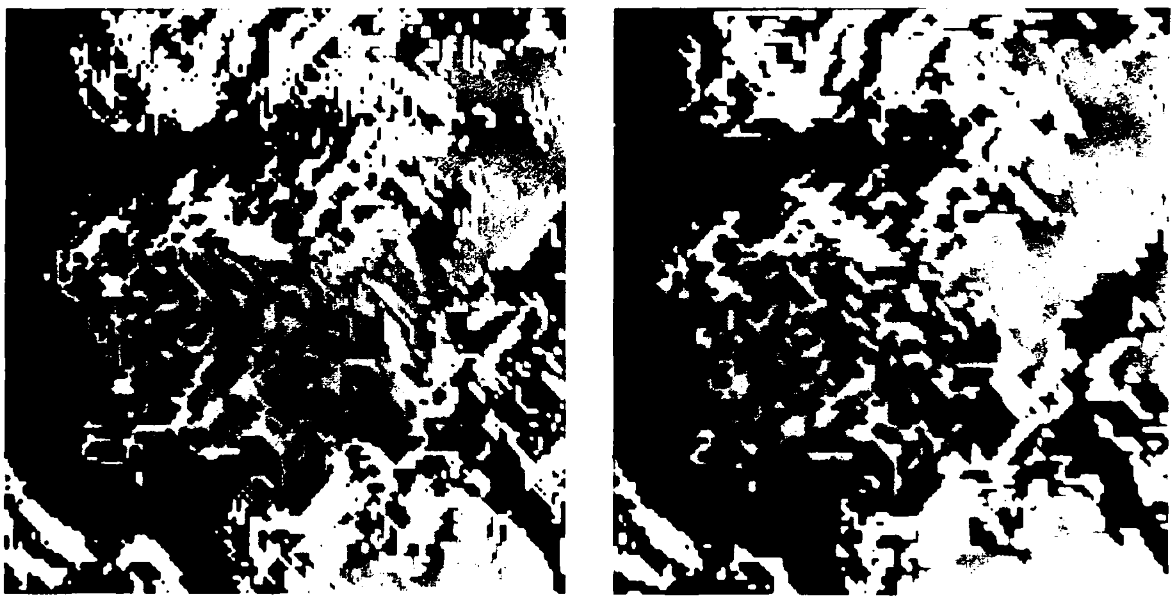
(a) URG06-R1-S45 (b) TIN06-S45

FIGURE 17 SLOPE MAPS--REGION 06



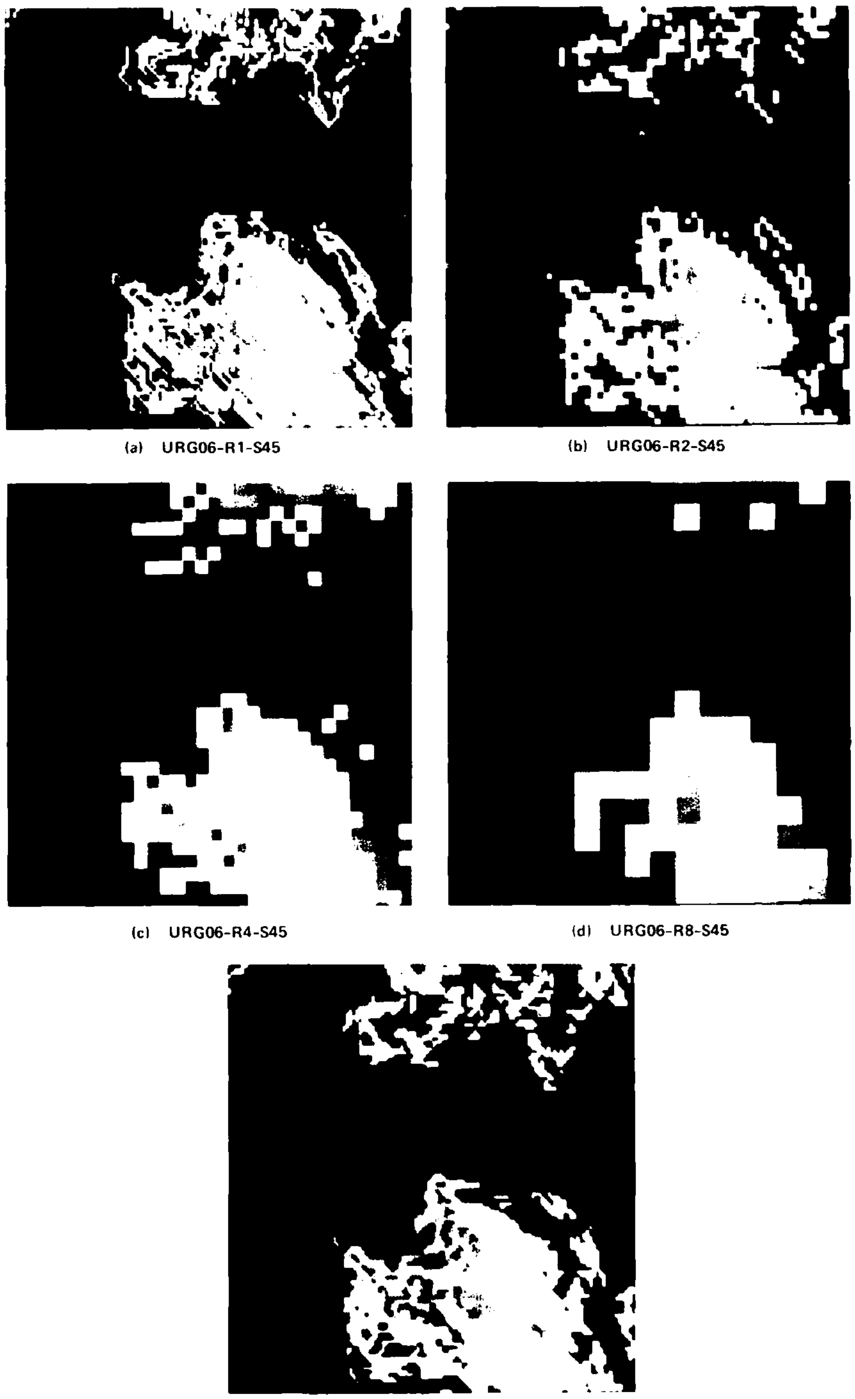
(a) URG07-R1-S45 (b) TIN07-S45

FIGURE 18 SLOPE MAPS--REGION 07



(a) URG14-R1-S45 (b) TIN14-S45

FIGURE 19 SLOPE MAPS--REGION 14



(a) URG06-R1-S45

(b) URG06-R2-S45

(c) URG06-R4-S45

(d) URG06-R8-S45

(e) TIN06-S45

FIGURE 20 SLOPE MAPS REGION 06 TIN AND URG DBs

area is shown as masked. For our evaluation, the truly masked and unmasked areas are given by the baseline URG DB results, we assume both errors are zero for this case.

Table 4 shows the visibility map errors for the six observation points and the four nonbaseline DBs (3 URGs and 1 TIN). The errors

Table 4

VISIBILITY MAP ERRORS

Observation Point	Type of Error	URG Errors (% of Total Region) R = 2	R = 4	R = 8	TIN Errors (% of Total Region)
1C	I	3.9	6.4	12.8	6.0
1C	II	0.9	1.2	1.8	2.4
1C	I + II	4.8	7.6	14.6	8.4
2N	I	2.1	3.3	6.3	1.0
2N	II	0.5	1.1	2.1	2.4
2N	I + II	2.6	4.4	8.4	3.4
2S	I	1.3	3.0	2.5	0.6
2S	II	0.3	0.4	0.9	1.7
2S	I + II	1.6	3.4	3.4	2.3
3C	I	9.0	2.8	11.9	7.3
3C	II	0.4	24.9	6.6	1.7
3C	I + II	9.4	27.7	18.5	9.0
4N	I	0.8	11.3	24.4	1.1
4N	II	9.4	1.5	1.5	2.8
4N	I + II	10.2	12.8	25.9	3.9
4S	I	4.8	9.4	23.7	1.5
4S	II	1.1	2.4	4.2	3.7
4S	I + II	5.9	11.8	27.9	5.2

are listed in percentage of the total region area which is 1600 m x 1600 m, or 2.56 million m^2. The errors range from a minimum of 0.3 percent for Type II, Observation Point 2S, and the R = 2 URG DB, to a maximum of 24.9 percent for Type II, Observation Point 3C, and the R = 4 URG DB.

TIN errors range from 0.6 percent to 7.3 percent. Overall, for Type I errors, the values range from 0.6 percent to 24.4 percent; for Type II errors, the values range from 0.3 percent to 24.9 percent.

Note that the maximum error did not occur for the R = 8 URG DB as one might expect. However, the next to maximum error case did occur for the R = 8 URG DB and had a value of 24.4 percent for Type I, Observation Point 4N. Thus, the case for Observation Point 3C was exceptional for the R = 4 URG DB. The problem arose because Observation Point 3C was on a peak at one of the baseline DB points. This peak point is included in the R = 2 URG DB but not in the R = 4 URG DB (nor in the R = 8 URG DB). Thus, the peak shifts in the DB and the observation point is no longer at the peak. In addition, the slope of the local terrain near the observation point decreases significantly. These local effects have a pronounced effect on the visibility map. The new peak will mask the sector aligned with the LOS from observation point to peak point, and the decreased local slope will bring in the local horizon in the opposite LOS direction, masking off a significant amount of terrain.

This type of result is illustrative of one of the problems with the URG representation of terrain data. The problem is how to determine the terrain height that must be encoded at each point in the selected grid. There are two basic approaches for sampling the source data at the selected grid points: undersampling and interpolating, or oversampling and some form of filtering. We adopted the first approach, selected only the data samples we needed, and deleted the remaining samples from the baseline DB. However, because the baseline DB provided us with an oversampling of points relative to the reduced resolution DBs, we might have employed some form of filtering to construct the required URG DBs.

An example of a smoothing filter is to average together a group of neighboring points. This approach would probably reduce the sensitivity of the local horizon angle to the DB, although the effect may still be quite significant. However, if the selection of the grid points for the reduced resolution DB were such that the peak point was

retained, the averaging approach would probably have a more significant effect on the local horizon than the simple sampling approach. It is not clear at this point whether the averaging or the simple sampling approach will lead to better statistical results over a variety of terrain regions and observation points. This type of comparison was beyond the scope of this evaluation.

For the slope map cases, a Type I error occurs if an area is truly above the slope threshold, but is shown as being below the slope threshold. Conversely, a Type II error occurs if an area is truly below the slope threshold, but is shown as being above the slope threshold. Tables 5 and 6 show the slope map errors for the four regions and the four nonbaseline DBs. Table 5 shows the errors for the 30-percent slope threshold case, and Table 6 shows the errors for the 45-percent threshold case. The errors in Table 5 range from a minimum of 1.6 percent for Type II, Region 05, and the R = 2 URG DB, to a maximum of 23.7 percent for Type II, Region 14, and the R = 8 URG DB. TIN DB errors range from 1.9 percent to 10.5 percent. Type I errors range from 2 percent to 13.5 percent, and Type II errors range from 1.6 percent to 23.7 percent. In Table 6, the 45-percent threshold case, the errors range from 2.3 percent for Type I, Region 05, and both R = 2 and R = 8 URG DBs, to a maximum of 26.2 percent for Type II, Region 07, and the R = 8 URG DB. TIN DB errors range from 3 percent to 13.6 percent. Type I errors range from 2.3 percent to 13.6 percent; the Type II errors range from 2.5 percent to 26.2 percent.

C. Computer Resource Measures

Computer resource measures were obtained by running the visibility and slope map programs on the IBM 370 computer at OSI. The OSI system provides a number of execution statistics with the completion of each job. The principal statistics follow:

(1) TCB Task control block Central Processing Unit (CPU) time
(2) SRB System resource block CPU time
(3) CPU Total task CPU time (TCB + SRB)

Table 5

30 PERCENT SLOPE MAP ERRORS

Region	Type of Error	URG Errors (Percent of Total Region)			TIN Errors (Percent of Total Region)
		R = 2	R = 4	R = 8	
05	I	2.0	2.9	2.6	3.1
05	II	1.6	3.1	6.1	1.9
05	I + II	3.6	6.0	8.7	5.0
06	I	3.6	4.3	7.1	5.1
06	II	2.9	5.9	9.2	4.1
06	I + II	6.5	10.2	16.3	9.2
07	I	7.9	11.6	13.5	8.7
07	II	6.7	11.1	17.1	9.6
07	I + II	14.6	22.7	30.6	18.3
14	I	6.7	9.1	10.4	10.2
14	II	7.0	13.1	23.7	10.5
14	I + II	13.7	22.2	34.1	20.7

Table 6

45 PERCENT OF SLOPE MAP ERRORS

Region	Type of Error	URG Errors (Percent of Total Region)			TIN Errors (Percent of Total Region)
		R = 2	R = 4	R = 8	
05	I	2.3	2.8	2.3	3.6
05	II	2.5	4.4	7.1	3.0
05	I + II	4.8	7.2	9.4	6.6
06	I	4.1	4.8	4.1	6.1
06	II	4.8	7.8	12.3	6.0
06	I + II	8.9	12.6	16.4	12.1
07	I	7.8	9.8	9.0	13.6
07	II	9.7	15.9	26.2	13.1
07	I + II	17.5	25.7	35.2	26.7
14	I	6.3	6.9	5.2	11.6
14	II	9.7	16.6	24.7	11.8
14	I + II	16.0	23.5	29.9	23.4

(4) VIRT The amount of virtual memory used by the problem program

(5) SYS The amount of system memory used to support the user

(6) RGN The total amount of memory required (VIRT + SYS)

(7) EXCP Number of input/output (I/O) channel program executions.

The I/O operations for all runs refers to I/O operations from disk. These plus other measures are employed in a formula to compute machine units used. The machine units are then used to bill the user. For all runs used in this evaluation, the only significant factors in the machine unit formula were CPU, RGN, and EXCP.

Table 7 lists the computer resource measures obtained in generating the visibility maps for six observation points and the five different DBs (including the baseline DB). The memory-used values are essentially constant for the URG DB and the TIN DB cases as we expected. The task specific memory (VIRT) was 236 and 212 for the URG and the TIN cases, respectively. Any variation in RGN seen in Table 7 corresponds to slight variations in system support memory (SYS) required for the TIN cases. The CPU times shown are dominated by the TCB task specific CPU times in all cases. The ratios of SRB to TCB range from about 0.03 to 0.08. Typically, the CPU times for the TIN cases fall between the R = 2 and R = 4 URG cases; the EXCPs are comparable to the R = 8 URG cases.

Table 8 lists the computer resource measures obtained in generating the slope maps for four regions, and five DBs. These values are independent of the slope threshold, because once the slope values are obtained, the identical operations remain to test against threshold values. Again, VIRT is constant for the URG and TIN cases and is equal to 176 and 512, respectively. Thus, whereas the values of VIRT were comparable for the visibility map problems, TIN required about 2.9 times the memory as URG. In all cases TIN required fewer EXCPs, and in most cases required less CPU time than URG. The one exception is for Region 07 in which TIN required a CPU time greater than the R = 8 URG case, but slightly less than the R = 4 URG case.

Table 7

VISIBILITY MAP COMPUTER RESOURCE MEASURES

Observation Point	Data Base (Type/R)	Run Time CPU (s)	Memory RGN (K bytes)	Input/Output EXCP
1C	URG/1	10.26	452	170
1C	URG/2	2.38	452	46
1C	URG/4	1.19	452	18
1C	URG/8	0.67	452	8
1C	TIN	1.46	436	8
2N	URG/1	9.64	452	143
2N	URG/2	2.96	452	44
2N	URG/4	1.22	452	18
2N	URG/8	0.69	452	8
2N	TIN	1.63	420	11
2S	URG/1	8.31	452	117
2S	URG/2	2.57	452	37
2S	URG/4	1.06	452	14
2S	URG/8	0.63	452	7
2S	TIN	1.29	420	8
3C	URG/1	8.71	452	135
3C	URG/2	2.89	452	46
3C	URG/4	1.20	452	19
3C	URG/8	0.70	452	9
3C	TIN	1.58	424	8
4N	URG/1	8.60	452	138
4N	URG/2	2.75	452	44
4N	URG/4	1.10	452	18
4N	URG/8	0.70	452	9
4N	TIN	1.65	424	8
4S	URG/1	9.25	452	153
4S	URG/2	3.14	452	54
4S	URG/4	1.34	452	22
4S	URG/8	0.73	452	10
4S	TIN	1.50	424	8

Table 8

SLOPE MAP COMPUTER RESOURCE MEASURES

Region	Data Base (Type/R)	Run Time CPU (s)	Memory RGN (K bytes)	Input/Output EXCP
05	URG/1	2.61	396	140
05	URG/2	1.47	396	78
05	URG/4	1.20	392	63
05	URG/8	1.16	396	59
05	TIN	0.71	712	19
06	URG/1	3.68	404	140
06	URG/2	1.93	392	78
06	URG/4	1.21	396	63
06	URG/8	1.14	396	59
06	TIN	1.06	724	22
07	URG/1	4.98	408	140
07	URG/2	2.01	396	78
07	URG/4	1.32	396	63
07	URG/8	1.15	396	59
07	TIN	1.28	728	25
14	URG/1	4.16	404	140
14	URG/2	1.79	424	78
14	URG/4	1.26	396	63
14	URG/8	1.15	396	59
14	TIN	1.04	700	22

D. Visibility Map Results

Plots of computer resource measures versus errors for the visibility map test problem are shown in Figures 21 and 22. Figure 21 shows the relationship between CPU time and test problem errors for the six observation points. Figure 22 shows the corresponding results for the number of I/O channel program executions (EXCPs). In each of these plots and subsequent plots showing the results of the evaluation, the error is plotted on the abscissa in percent of total region area, while the computer resource measures are plotted on the ordinate. Data points generated from the URG DBs are shown by open circles, and those from the TIN DB are shown as Xs. Three results are shown in each plot: Type I errors, Type II errors, and the sum of Type I and II errors.

Comparison of TIN results to URG results is accomplished by comparing the computer resources required to obtain equal error results. The better performer with respect to a given computer resource measure requires a lower value of that measure. This comparison is indicated in the plots by a vertical arrow from the URG curves to the TIN datapoint. An arrow pointing upward indicates better performance for the URG DB, while an arrow pointing downward indicates better performance for TIN. Because a logarithmic ordinate scale is used, the length of the arrow gives the relative improvement factor.

In certain cases, the URG DB errors did not reach the level of the TIN errors, but extrapolation allows a fairly conclusive qualitative comparison of the results. The appropriate arrows have been drawn in these cases, and improvement factors have been inferred by extrapolation of URG curves. In other cases (notably for Observation Points 3C and 4N), the errors did not increase monotonically with decreasing resolution. These cases occur if certain critical grid points (such as local peak points) are deleted from the baseline URG DB to degrade the resolution. As discussed in Section VI.B., this can significantly modify the local horizon and dramatically increase or decrease the test problem errors. In the case of Observation Point 3C, the Type I errors first increase, then decrease, then increase again (see Figure 21(d)). If we assume

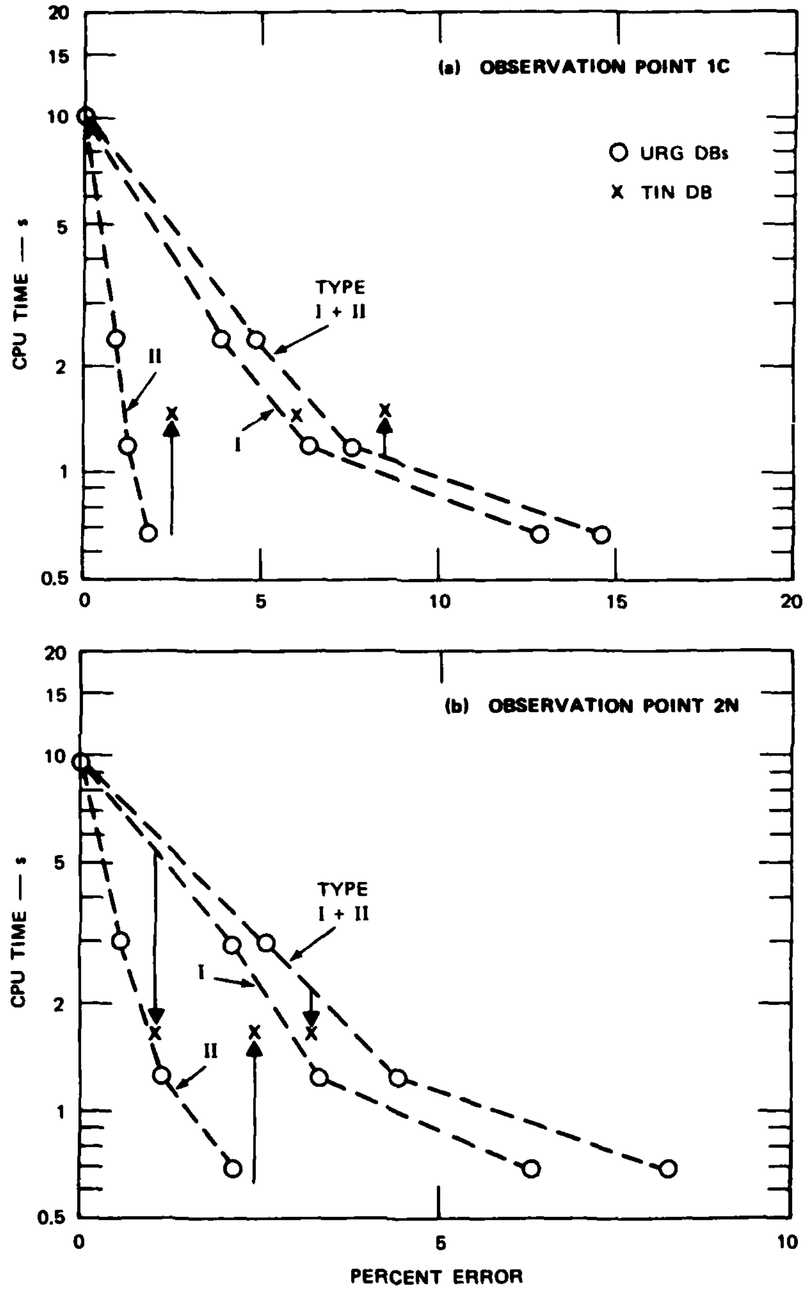


FIGURE 21 VISIBILITY MAP RESULTS--CPU TIME

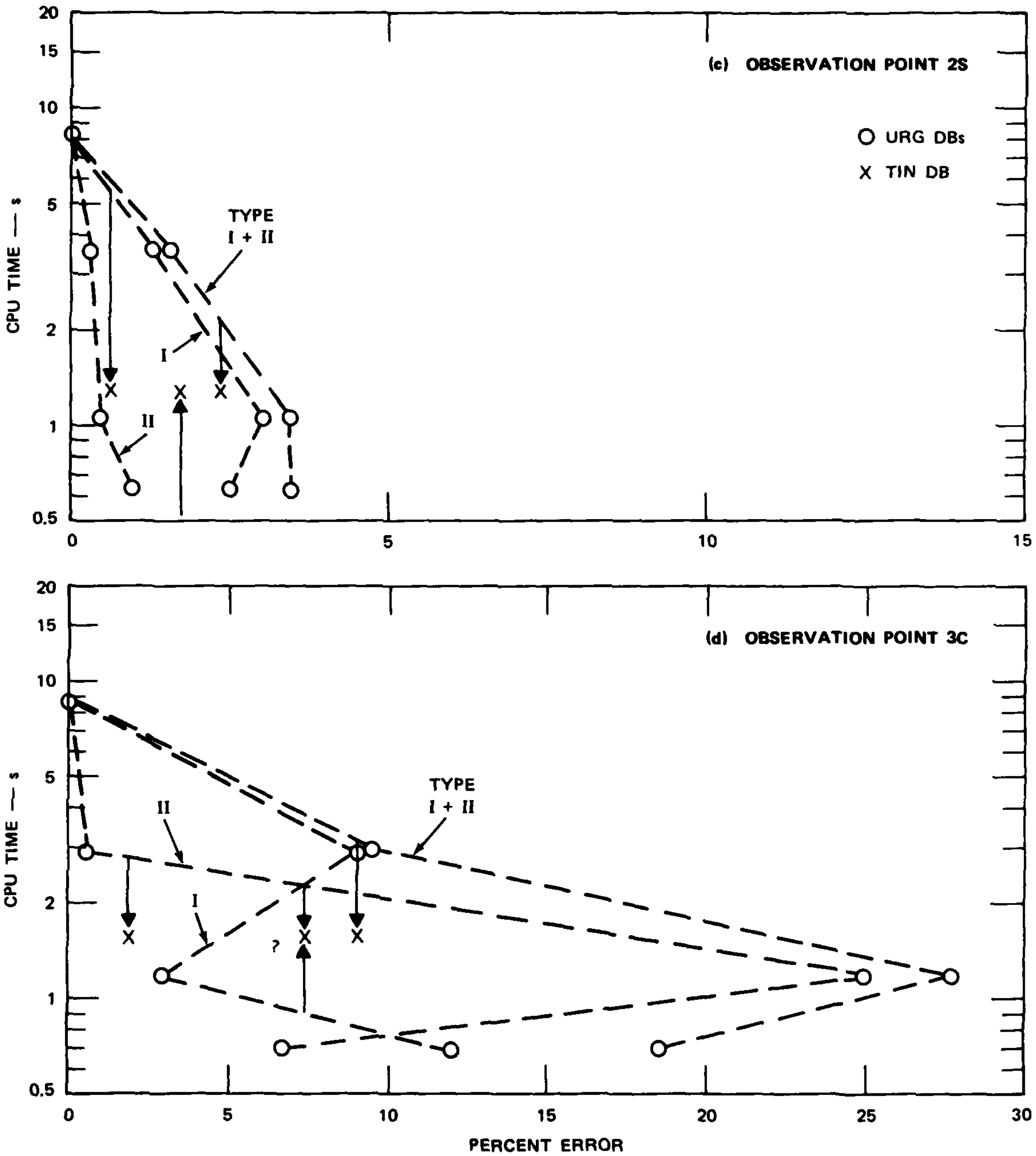


FIGURE 21 CONTINUED

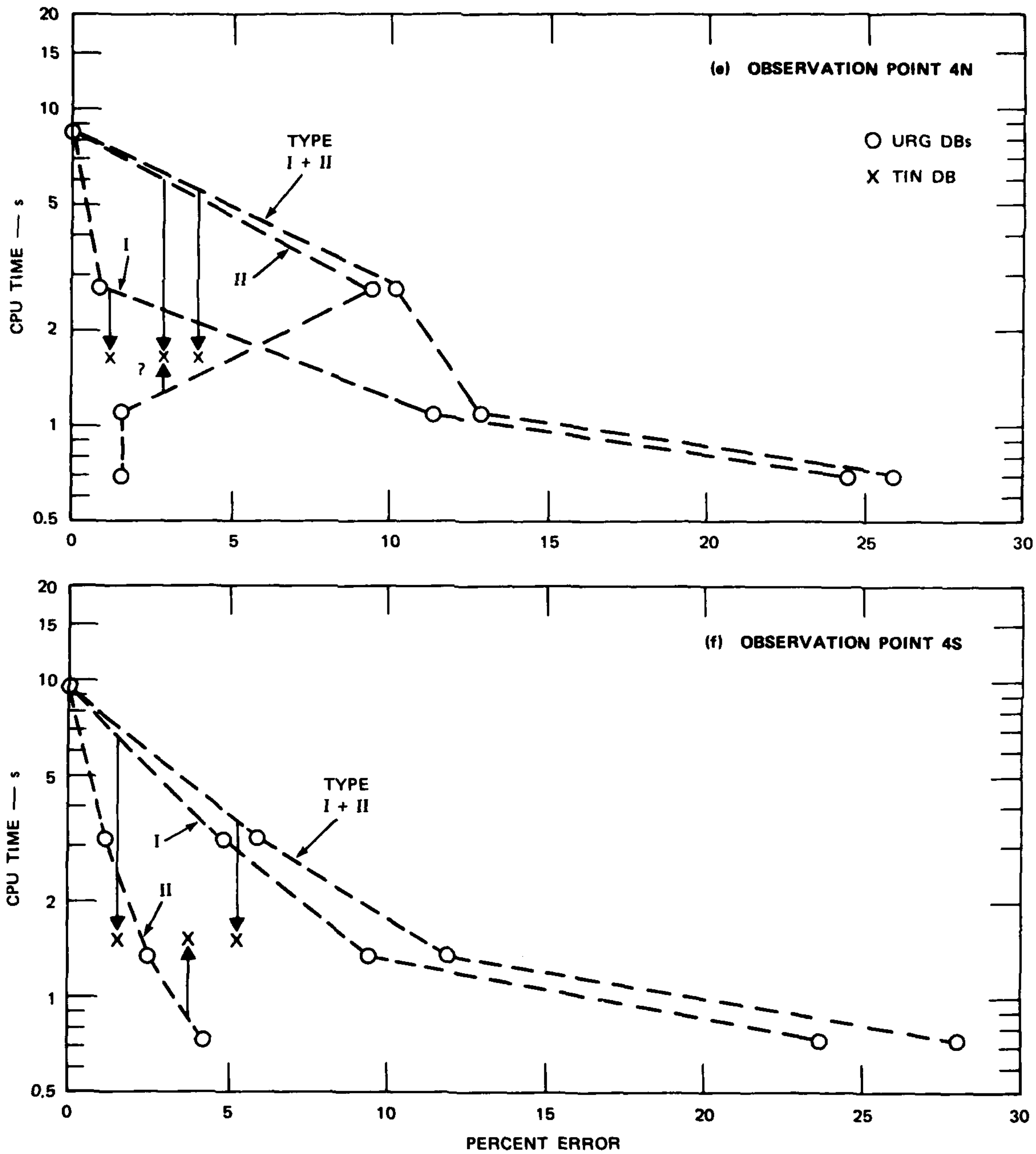


FIGURE 21 CONCLUDED

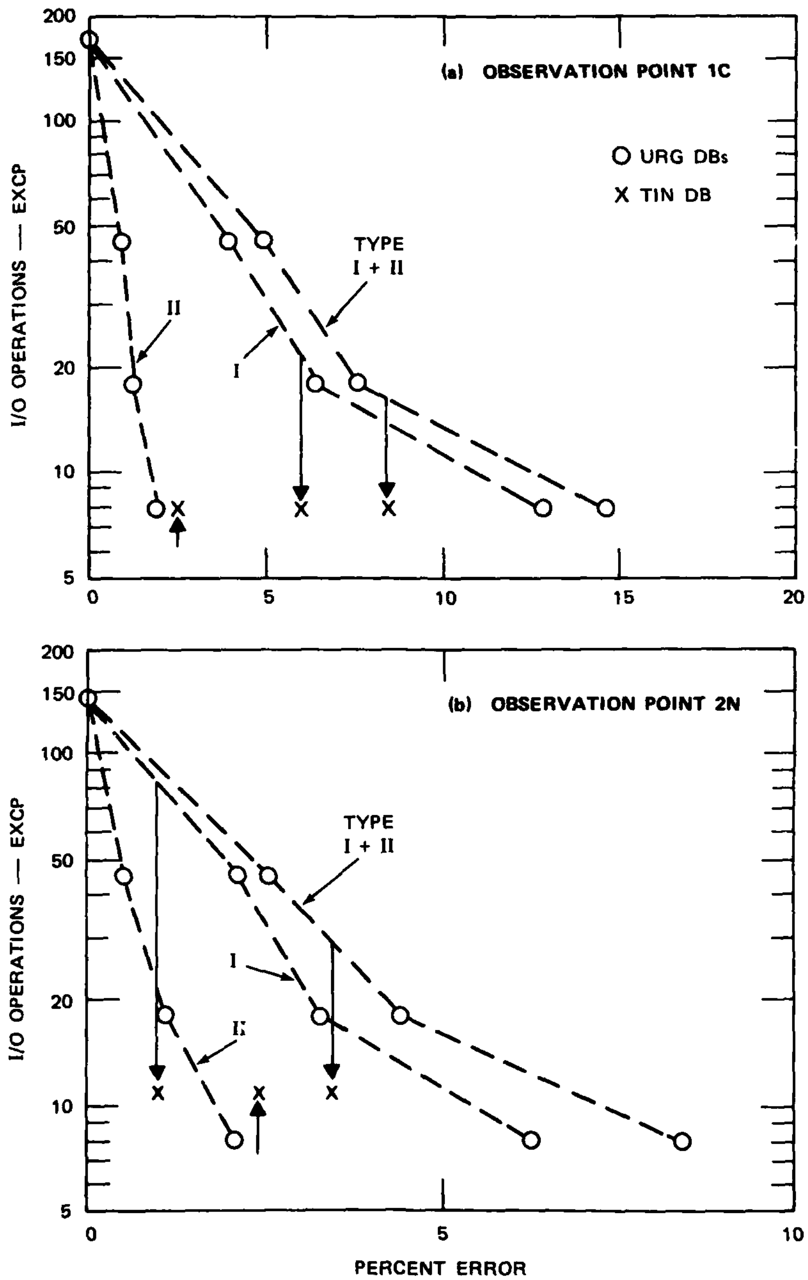


FIGURE 22 VISIBILITY MAP RESULTS--I/O OPERATIONS

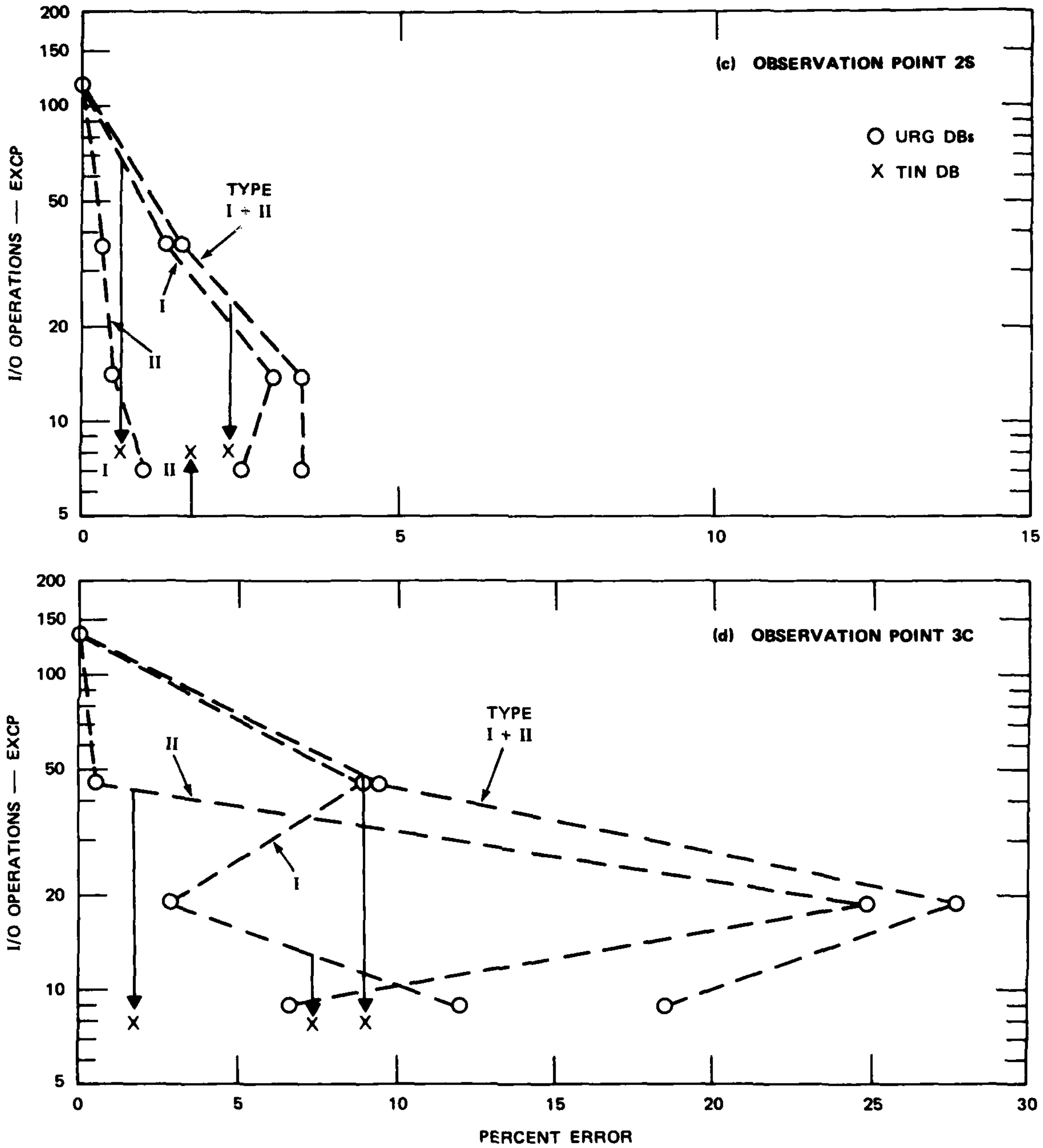


FIGURE 22 CONTINUED

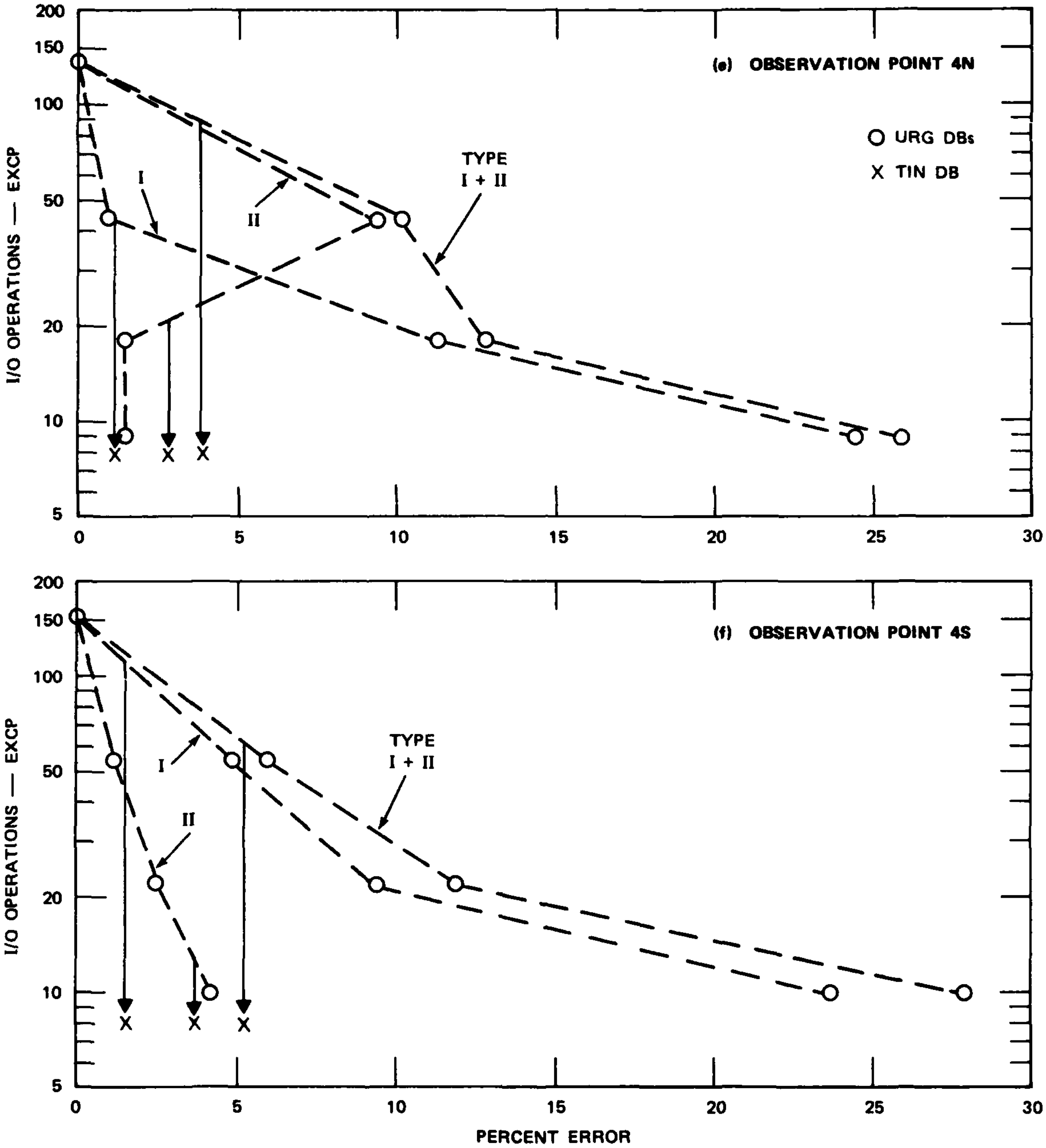


FIGURE 22 CONCLUDED

continuity, the URG curve is S-shaped and the TIN data point lies below one portion of the curve and above another portion. Similar effects occur for Type II results for Observation Point 4N (see Figure 21(e)). In these cases, two arrows with a question mark have been drawn in the plots.

The total error curves (Type I + II) are generally much better behaved. In all but the case of Observation Point 3C, total errors increase monotonically with decreasing resolution.

The results are tabulated in Table 9 by listing the performance improvement factors and the better performing DB for the six observation points and the three different error measures. If dual improvement factors exist, Table 9 lists both. Improvement factors estimated by extrapolation are so identified. In addition, the average improvement factors for TIN and URG cases are included. Because dual improvement factors occur, dual average values are also shown.

Thus, in terms of CPU time, the TIN performed better in Type I and total errors in 5 out of 6 cases. URG performed better in 4 out of 6 cases in Type II errors. For Type I and II errors, these numbers are modified slightly in favor of the URG if the alternate set of possible improvement factors are considered. Improvement factors for the total error cases that favored TIN ranged from 1.7 to 3.4 and averaged 2.1. In the single total error case (Observation Point 1C) that favored URG, the improvement factor was 1.3.

Table 10 gives the results shown in Figure 22 for EXCPs. These results show that in most cases TIN performed better in terms of EXCP. For Observation Points 3C and 4N, at which dual improvement factors favoring the same DB are indicated, the lower improvement factors are given. In terms of EXCPs, TIN performed better in Type I and total errors in 6 out of 6 cases. In Type II errors, TIN performed better in only 3 out of 6 cases--an even split with URG. However, the TIN average improvement factor was significantly better in Type II errors--3.2 for TIN versus 1.7 for URG. In both Type I and total errors, the TIN improvement factor was 5.5.

Table 9

VISIBILITY MAP CPU IMPROVEMENT FACTORS

Observation Point	Type I Errors	Type II Errors	Type I + II Errors
1C	URG/1.1	URG/3.0 (est.)	URG/1.3
2N	TIN/3.3	URG/3.0 (est.)	TIN/1.3
2S	TIN/4.2	URG/3.0 (est.)	TIN/1.7
3C	TIN/1.5 or URG/1.8	TIN/1.8	TIN/2.0
4N	TIN/1.7	TIN/3.6 or URG/1.3	TIN/3.4
4S	TIN/4.4	URG/1.8	TIN/2.3
TIN favored cases	5 or 4	2 or 1	5
URG favored cases	1 or 2	4 or 5	1
TIN average value	3.0 or 3.4	2.7 or 1.8	2.1
URG average value	1.1 or 1.5	2.7 or 2.4	1.3

Table 10

VISIBILITY MAP EXCP IMPROVEMENT FACTORS

Observation Point	Type I Errors	Type II Errors	Type I + II Errors
1C	TIN/2.6	URG/1.5 (est.)	TIN/2.1
2N	TIN/7.5	URG/1.8 (est.)	TIN/2.7
2S	TIN/8.0	URG/1.8 (est.)	TIN/3.1
3C	TIN/1.7	TIN/5.5	TIN/6.0
4N	TIN/5.5	TIN/2.6	TIN/11.0
4S	TIN/7.5	TIN/1.5	TIN/7.8
TIN favored cases	6	3	6
URG favored cases	0	3	0
TIN average value	5.5	3.2	5.5
URG average value	-	1.7	-

Comparisons between TIN and URG have so far only considered the inferred computer resource measure differences between the two cases for an equal error level. However, an additional factor that must also be considered in comparing the two methods is the required DB storage for equal error levels. This information can also be inferred from Figures 21 and 22 by estimating the URG resolution factor that would have been required to match the TIN error level. Linear interpolation of the total error results give the equivalent resolution factors shown in Table 11.

Table 11

DATA BASE STORAGE COMPARISONS
FOR VISIBILITY MAP GENERATION

Observation Point	Region	Equivalent URG Resolution Factor R	Ratio of TIN to Equivalent URG Storage
1C	06	4.5	15.1
2N	07	2.9	11.2
2S	06	2.8	5.8
3C	06	2.0	3.0
4N	14	1.4	3.3
4S	14	1.9	6.0
Average Values		2.6	7.4

If the equivalent URG resolution factors are given, the ratio of the TIN storage requirements to the equivalent URG storage requirements can be computed. These are also shown in Table 11. The required storage ratios range from 3.0 to 15.1, all favoring the URG DB. The average value is about 7.4. Thus, it is clear that the overhead cost for TIN DB storage is a very significant factor. Note that the equivalent storage ratios had large variations for Region 06, where a fairly large amount of the terrain is relatively flat. The two storage ratios for Region 14, a much hillier area and the one requiring the most TIN points, were comparable to the two lower storage ratios for Region 06. Initially we

might expect that the storage ratios for Region 14 should be significantly higher than the storage ratios for Region 06 because Region 14 required more TIN points. Evidently, the greater number of TIN points for Region 14 also improved its error performance relative to the URG as indicated by the low equivalent URG resolution factors.

One possible combined computer resource measure is provided by the OSI billing algorithm, which computes a quantity called machine units (MU). A simplified version of the MU formula that retains only the significant terms is:

$$MU = \left(K_1 \times CPU + K_2 \times EXCP\right) \times \left(1 + K_3 \times DA + K_4 \times RGN\right)$$

where DA denotes the number of disks allocated and the coefficients are:

K_1 = 1.583 for CPU in seconds

K_2 = 0.0002

K_3 = 0.05

K_4 = 0.0008 for RGN in kilobytes.

The only factor not previously discussed is DA. Values of DA were essentially constant for each test problem and each DB case. They ranged from 3 to 5. Thus, this factor has a significant effect on the values of MU that one might compute, but not on the comparability of TIN versus URG. For both the TIN and URG cases, the value of the terms in the rightmost parentheses was essentially 1.5. Thus, the MU formula can be written as:

$$MU \simeq 2.37 \times CPU + 0.0003 \times EXCP$$

Because CPUs range from about 0.67 s to about 10 s, while EXCPs range from about 8 to 170, the EXCPs are not a significant factor in computing MU. Thus, MU is not significant as a combined measure of CPU and EXCP. No further effort was made to define a combined measure in view of the fact that the total error results both favored the TIN method.

E. Slope Map Results

Plots of computer resource measures versus errors for the slope map test problem are shown in Figures 23 through 26. Figures 23 and 24

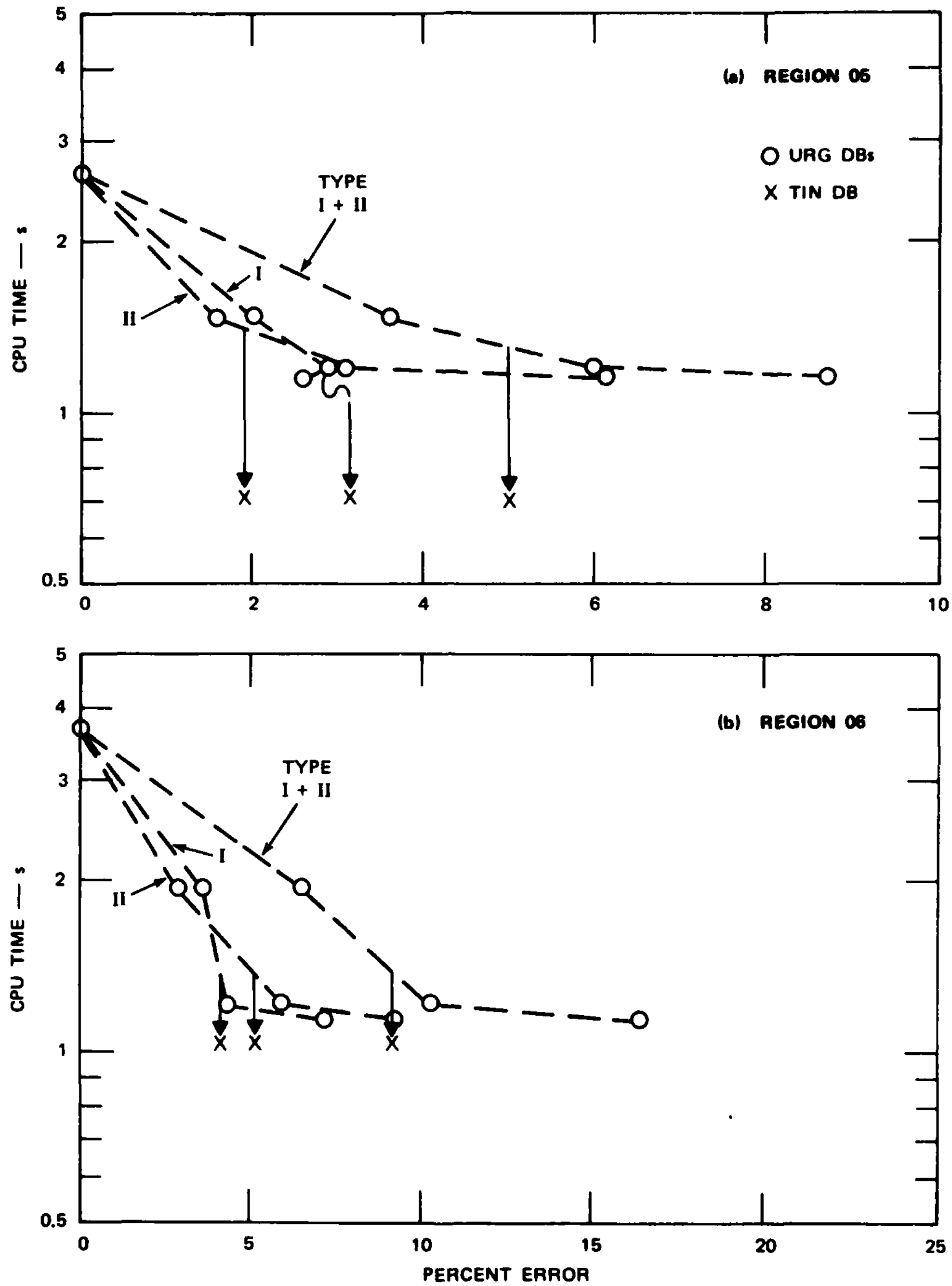


FIGURE 23 SLOPE MAP RESULTS--30 PERCENT SLOPE--CPU TIME

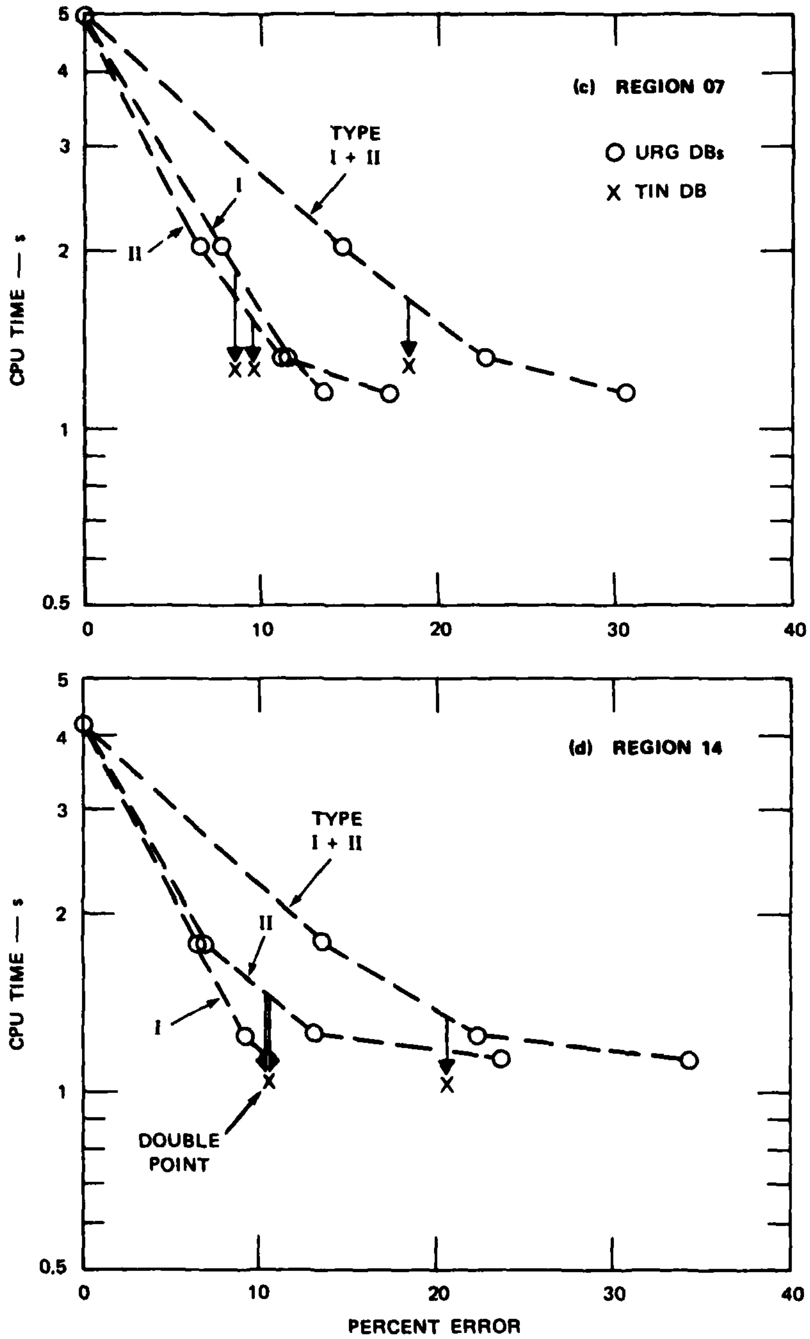


FIGURE 23 CONCLUDED

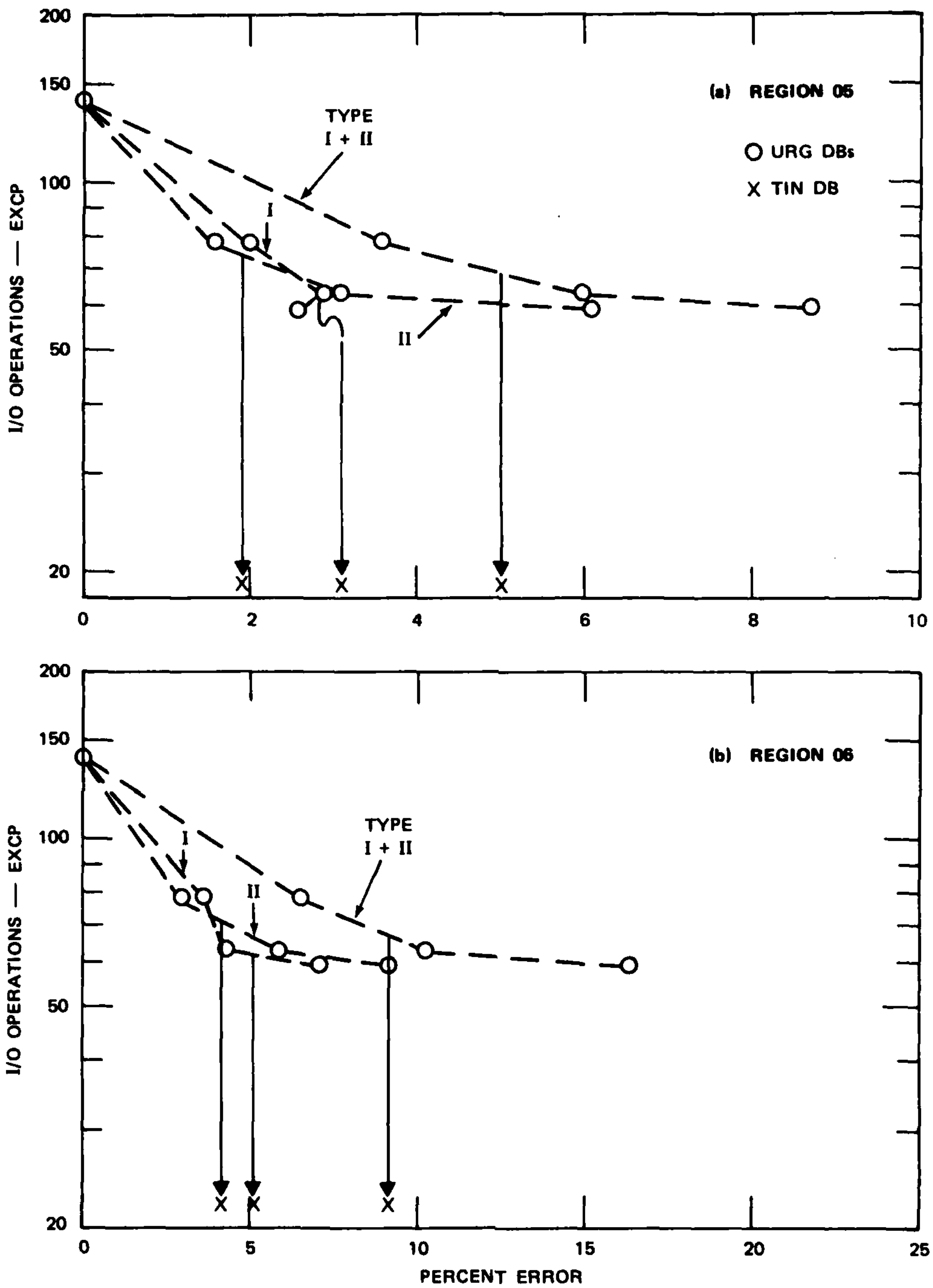


FIGURE 24 SLOPE MAP RESULTS--30 PERCENT SLOPE--I/O OPERATIONS

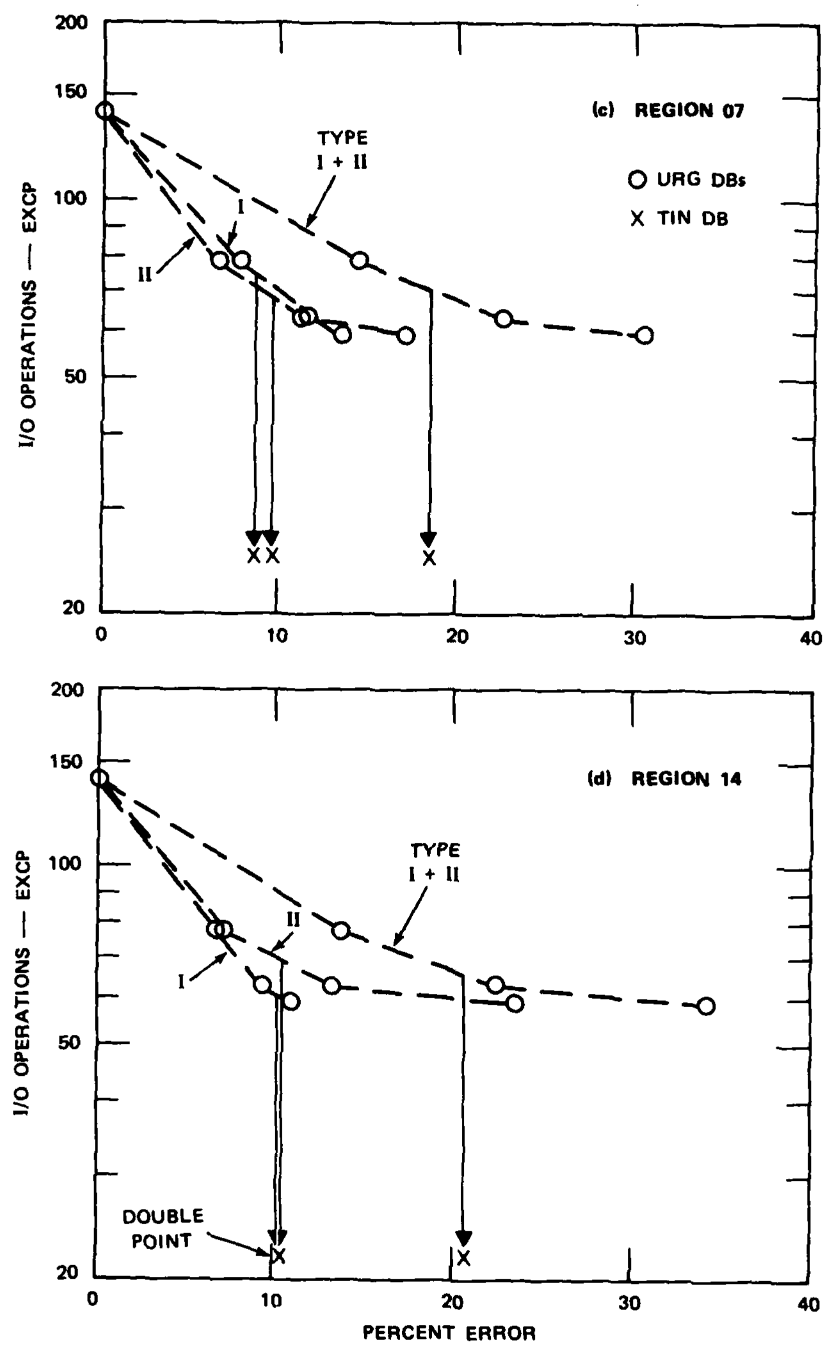


FIGURE 24 CONCLUDED

are for the 30-percent slope threshold cases, while Figures 25 and 26 are for the 45-percent slope threshold cases. A review of these plots shows that in many cases, the Type I URG errors reach a maximum and then began to decrease. This systematic effect occurs as the resolution of the URG DB is decreased.

Decreasing the URG resolution by deleting points has the effect of decreasing the higher, computed slope values and increasing the lower, computed slope values. Initially, if relatively few points have been deleted, the errors of Type I and II may both increase. However, in the extreme as more and more points are deleted, we expect that the area above the slope threshold will approach zero if the slope threshold is sufficiently high. As the slope threshold approaches zero, the Type I errors must also approach zero, and Type II errors are maximized. The higher the slope threshold, the sooner the reversal of the Type I errors will be seen. If we compare the 30-percent slope threshold cases in Figures 23 and 24 to the 45-percent slope threshold cases in Figures 25 and 26, we do indeed see this effect for all 45-percent slope cases and only once for the 30-percent slope cases. Similar effects will also occur if average slope values are used instead of deletion of points to obtain the lower resolution DB.

For the 30-percent slope threshold cases, the TIN results for the Type I errors of Region 05 fell very close to the maximum URG Type I error, and the corresponding computer resource measures were very significantly different, favoring the TIN. Thus, we indicate a performance improvement factor for TIN in these cases and estimate the amount of improvement by assuming equal errors for TIN and URG. Table 12 gives these results for CPU time and Table 13 for EXCPs. The TIN results are always better and the improvement factors range from 1.4 to 1.5 for CPU time and 3.0 to 3.2 for EXCPs.

For the 45-percent slope threshold cases (shown in Figures 25 and 26), Type I errors for the URG DBs reached maxima that were less than the TIN Type I errors. Because the differences between TIN errors and the maximum URG errors were more significant than for the 30 percent slope case, we cannot say that comparability has been reached for Type I

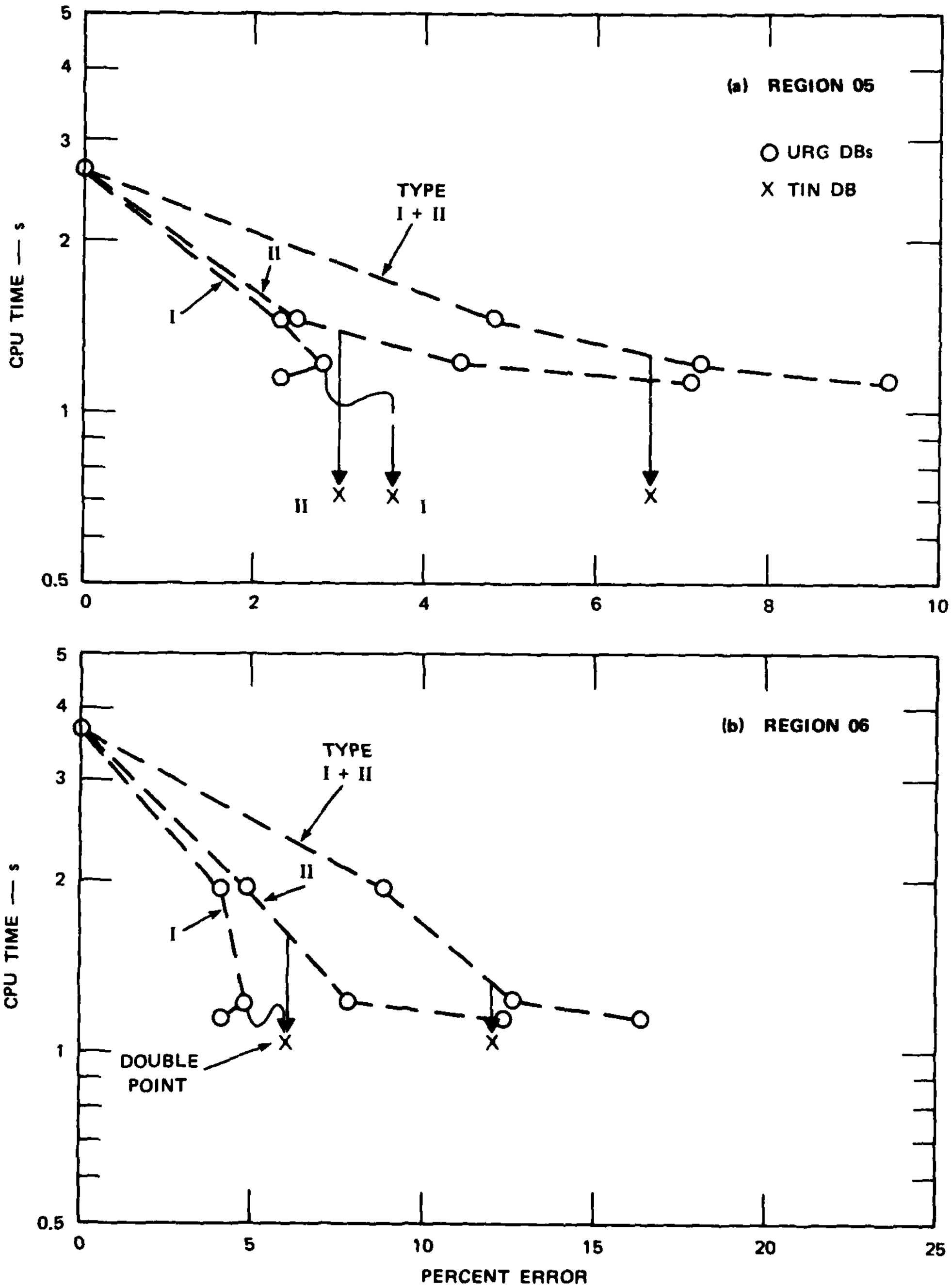


FIGURE 25 SLOPE MAP RESULTS--45 PERCENT SLOPE--CPU TIME

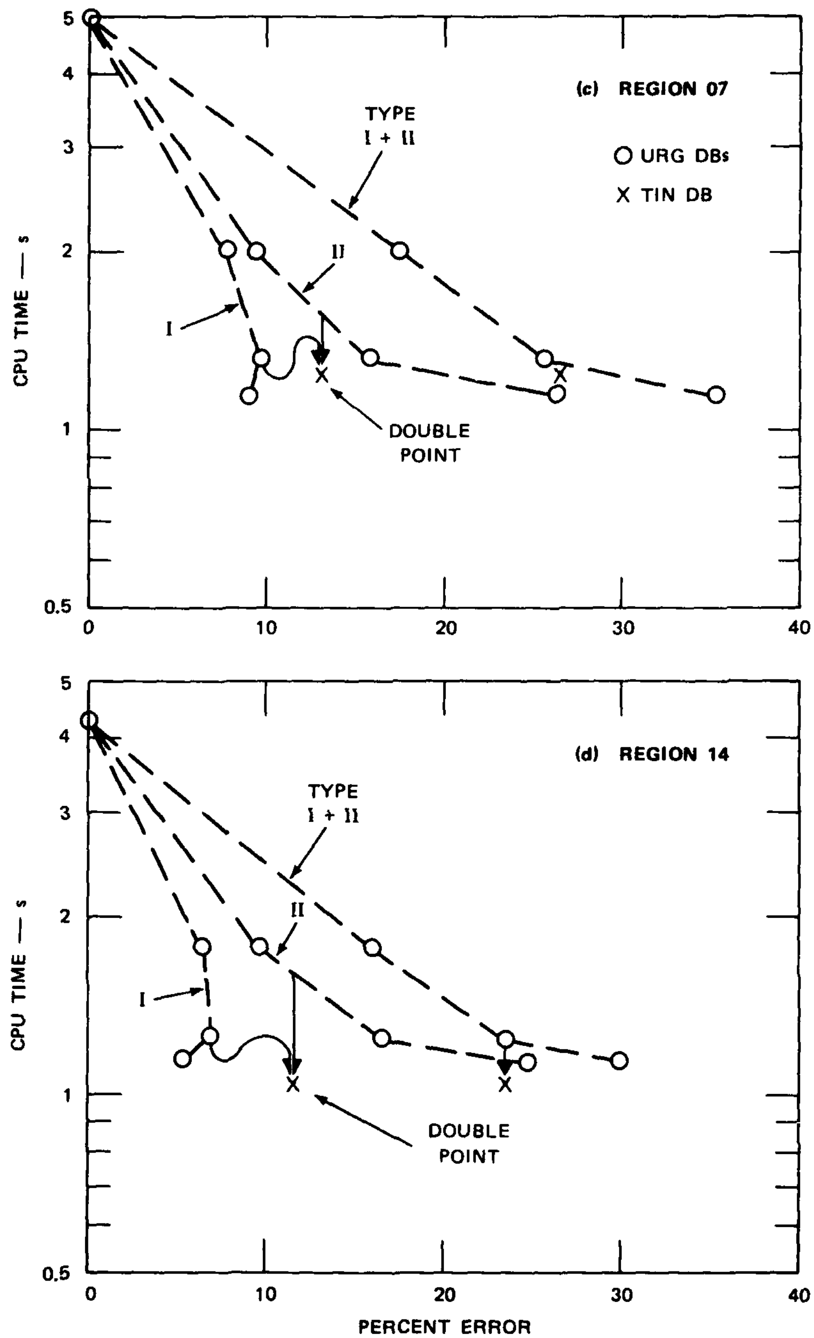


FIGURE 25 CONCLUDED

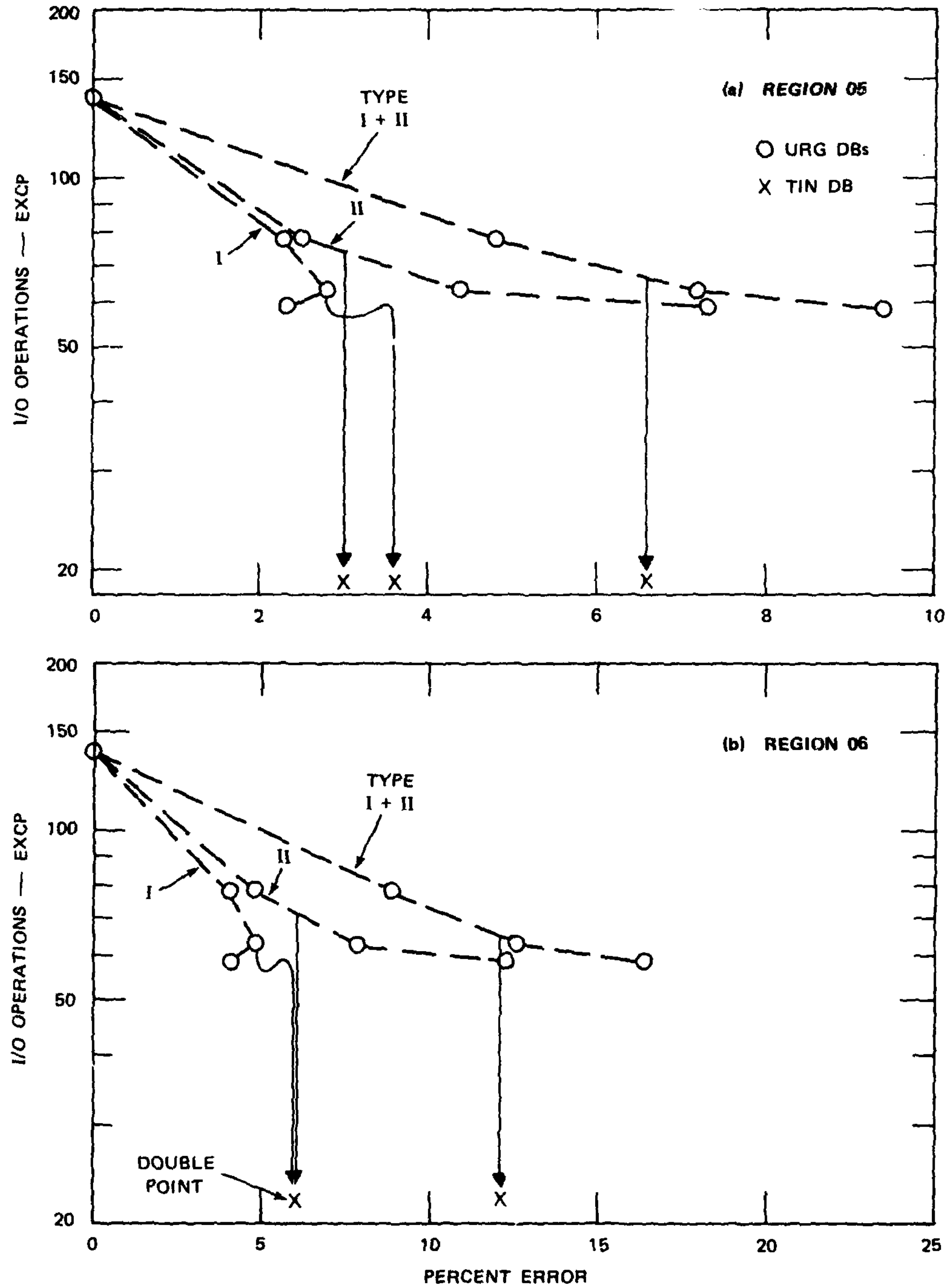


FIGURE 26 SLOPE MAP RESULTS--45 PERCENT SLOPE--I/O OPERATIONS

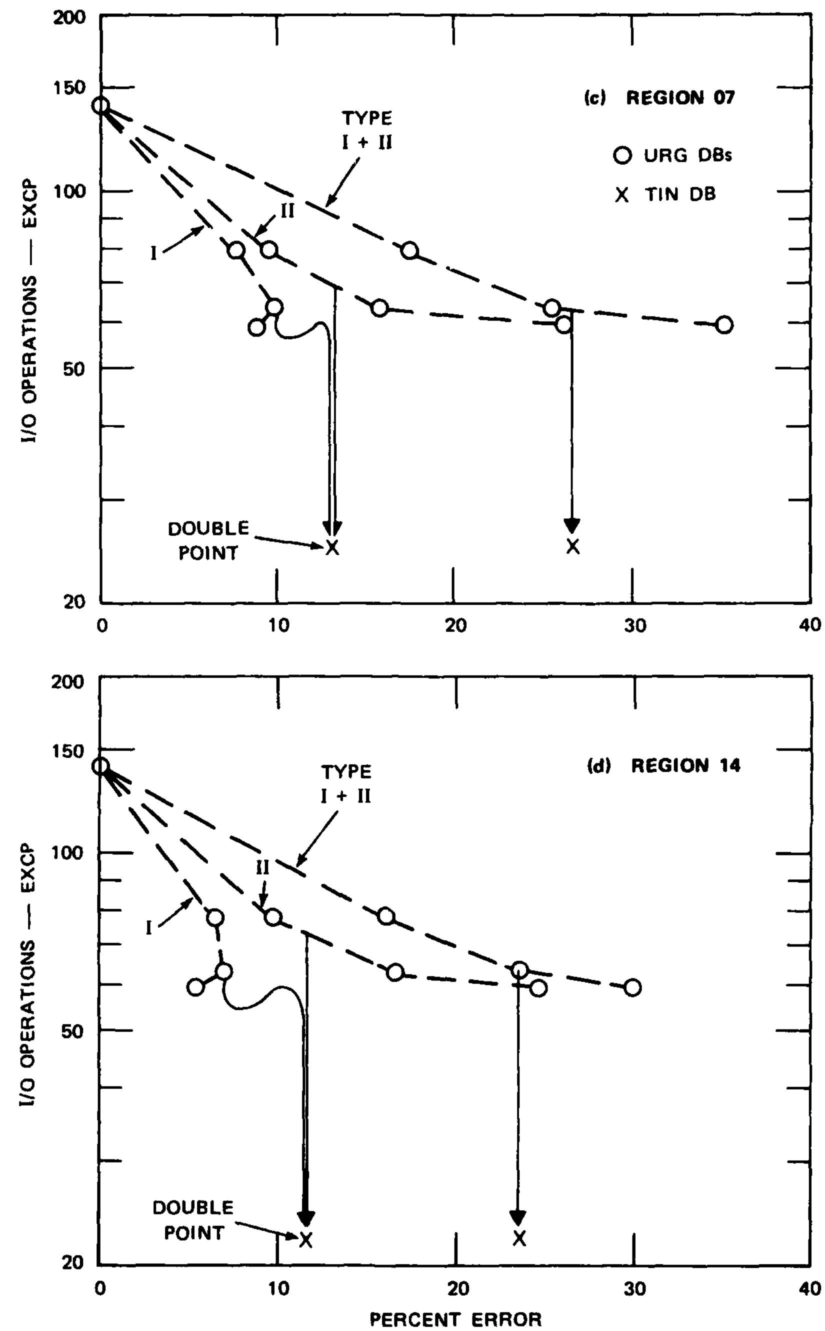


FIGURE 26 CONCLUDED

Table 12

SLOPE MAP CPU IMPROVEMENT FACTORS--30 PERCENT SLOPE

Region	Type I Errors	Type II Errors	Type I + II Errors
05	TIN/1.7	TIN/2.1	TIN/1.8
06	TIN/1.3	TIN/1.3	TIN/1.4
07	TIN/1.5	TIN/1.2	TIN/1.3
14	TIN/1.1	TIN/1.4	TIN/1.3
TIN favored cases	4	4	4
URG favored cases	0	0	0
TIN average value	1.5	1.4	1.5
URG average value	-	-	-

Table 13

SLOPE MAP EXCP IMPROVEMENT FACTORS--30 PERCENT SLOPE

Region	Type I Errors	Type II Errors	Type I + II Errors
05	TIN/3.4	TIN/3.8	TIN/3.7
06	TIN/2.8	TIN/3.2	TIN/3.1
07	TIN/3.0	TIN/2.7	TIN/2.8
14	TIN/2.8	TIN/3.2	TIN/3.0
TIN favored cases	4	4	4
URG favored cases	0	0	0
TIN average value	3	3.2	3.2
URG average value	-	-	-

errors. In several cases comparability in a dual sense was achieved. That is, for a given level of computer resources (CPU time) we can compare the amount of Type I error generated by the TIN and URG DBs. However, because the method of constructing the URG DBs eventually forces Type I errors toward zero, the validity of making Type I error comparisons is questionable.

Table 14 shows the equivalent URG resolution factors and storage ratios for comparable total error performance of both TIN and URG for the 30-percent slope case. The storage ratios range from 3.8 to 22.9 and have an average value of 11.8. These results follow the increase in TIN points required for each of these regions. The combined effect of TIN overhead storage costs and relative error performance of TIN versus URG results in a significant DB storage advantage for the URG.

Table 14

DATA BASE STORAGE COMPARISONS
FOR 30 PERCENT SLOPE MAP GENERATION

Region	Equivalent URG Resolution Factor R	Ratio of TIN to Equivalent URG Storage
05	3.2	3.8
06	3.5	9.1
07	2.9	11.2
14	3.7	22.9
Average Values	3.3	11.8

Tables 15 and 16 give the results for the 45-percent slope map cases. Type I errors are not included, since comparability was not achieved in this measure. Table 15 shows the CPU times and that TIN performed better in all cases with an average improvement factor of 1.3 for the total error cases. Table 16 shows the EXCP results and also that TIN performed better in all cases with an average improvement factor of 3.

Table 15

SLOPE MAP CPU IMPROVEMENT FACTORS--45 PERCENT SLOPE

Region	Type II Errors	Type I + II Errors
05	TIN/2.0	TIN/1.8
06	TIN/1.6	TIN/1.3
07	TIN/1.3	TIN/1.05
14	TIN/1.5	TIN/1.2
TIN favored cases	4	4
URG favored cases	0	0
TIN average values	1.6	1.3
URG average values	-	-

Table 16

SLOPE MAP EXCP IMPROVEMENT FACTORS--45 PERCENT SLOPE

Region	Type II Errors	Type I + II Errors
05	TIN/3.9	TIN/3.5
06	TIN/3.3	TIN/3.0
07	TIN/2.8	TIN/2.5
14	TIN/3.4	TIN/2.9
TIN favored cases	4	4
URG favored cases	0	0
TIN average value	3.4	3
URG average value	-	-

Table 17 shows the storage comparison data for the 45-percent slope case. The storage ratios range from 4.6 to 26.7 and have an average value of 16.8. These results are similar to the 30-percent slope case, and again show a storage requirement advantage for the URG DB.

Table 17

DATA BASE STORAGE COMPARISONS
FOR 45 PERCENT SLOPE MAP GENERATION

Region	Equivalent URG Resolution Factor R	Ratio of TIN to Equivalent URG Storage
05	3.5	4.6
06	3.7	10.1
07	4.4	25.7
14	4.0	26.7
Average Values	3.9	16.8

VII CONCLUSIONS AND RECOMMENDATIONS

A conclusive comparative evaluation of competing DTMs such as the TIN and URG is a most difficult and, as yet, not a completely solved problem. The difficulties are at two levels. First of all, the eventual application of the DTM must be considered. There are many areas of application, and within each area, there are many specific types of problems that must be solved. A given DTM may work better than another in one application area, but not in another. Even within a given application a given DTM may work better on one type of problem than another. At the second level, for any given problem, there are multiple important measures of performance (MOPs) that cannot functinally be combined into a single objective. Data base (DB) storage requirements, problem computer resource requirements, and problem solution performance measures are several important MOPs applicable to specific problem solutions. Computer resource measures include such factors as the CPU time, the software core memory required, and the I/O program executions. For the test problems selected for this evaluation, performance measures consist of areal error measures of Type I and Type II, and the sum of these measures. The determination of a combined objective function accounting for all of these types of MOPs was beyond the scope of this study.

A. Conclusions

The principle objective of this evaluation was to select specific tactical test problems in the context of Marine Corps ground combat operations, and explore and compare the effects of TIN and URG DB on individual computer resource measures and problem solution error measures. The following conclusions are indicated by the results obtained:

(1) The TIN DB storage requirements are significantly higher than the URG DB storage requirements for equal total error performance. This conclusion is based on a small set of terrain samples employed in the study. These samples did not include terrain regions that were relatively

flat or gently rolling. Such cases are expected to require fewer TIN points for accurate representation, and thus, may have provided cases more favorable to TIN in terms of storage requirements. Depending on the necessity of minimizing the DB storage requirements, the TIN DB encoding overhead can be a major factor and a significant disadvantage for TIN.

(2) For the slope map problem the DB storage ratios correlate fairly well with the terrain elevation variability within the selected regions. The TIN DB storage requirements ranged from about 4 to 27 times the URG DB storage requirements for these cases.

(3) For the visibility map problem, the URG DB storage requirements were again significantly less than that for TIN, but the storage ratios no longer correlated highly with elevation variability alone. As more TIN points are required to model a highly variable terrain of a region, the better the TIN models the features important for accurate visibility mapping. Thus, the error performance improves and forces the equivalent URG to have a higher resolution. The TIN DB storage requirements ranged from about 3 times to about 15 times the URG DB storage requirements for these cases.

(4) The primary MOPs for comparing computer resources were CPU time and I/O program executions. The results generally favored the TIN DB over the URG in the computer resources required for a given level of error. In all cases but one, the visibility map for Observation Point 1C, TIN required less CPU time and fewer I/O program executions for a given level of total error (Type I plus Type II).

(5) For the slope map problem, the TIN DB consistently required fewer computer resources than the URG DB for a given level of error.

(6) For the visibility map cases, the TIN DB again consistently required fewer computer resources than the URG DB for a given level of total error. The Type I error comparisons generally favored the TIN DB , and Type II error comparisons generally favored the URG DB. However, the average computer resource improvement factors for those cases favoring TIN were generally higher than for those cases favoring URG.

Overall, these results indicate that although the TIN DB has high storage overhead compared to the URG DB, it performs well in conserving computer resources when employed to generate terrain slope and visibility maps. The general validity of this conclusion is limited by several important factors:

(1) the small number of cases analyzed

(2) the single TIN performance point for each case

(3) the TIN system employed to generate the TIN DBs was not an optimized production system.

These limitations were recognized in planning this comparative evaluation study. The small number of cases is a limitation that eventually should be addressed, once a suitable and fairly comprehensive comparative evaluation method has been developed. This study has provided the basis for such a method.

A present weakness of the evaluation method is the employment of a single TIN DB and its associated performance point for comparison. The problem is that we cannot generate a specific DB whether it be in the TIN or URG family, that will perform with a given error measure level on a specific tactical problem. If we happen to select a DB that results in too high an error level (one that fails to meet the accuracy requirements of the tactical user), we are not necessarily able to infer how the competing DTMs will compare at a satisfactory or desired error level. A similar problem exists if we are forced to compare DTMs at too low an error level.

The answer to this problem is to be able to set the parameters of DTMs so that two curves are obtained that span the desired range of error levels. We will then be able to select the error levels at which to compare the competing DTMs.

Finally, the programs, which fit a TIN model to a grid model, are very much prototypes and can be vastly improved. In fact, the experience of this comparison has been very helpful in determining the effectiveness of these procedures. The performance of the TIN model is affected not only by the efficiency of the programs operating on the TINs, but also by the number of points in the TIN representation of the grid. If the number of points can be significantly reduced, then the comparison will be favorably affected.

In the TIN construction process, the set of ridges and channels in that grid representation is first extracted. Points at significant

bends in these features are used as inputs to a TIN construction program. This TIN model is then compared with the grid and additional points are added to the TIN to reduce the differences until they meet the specifications.

Several improvements are possible. First, as it stands, the initial TIN approximation from the ridge and channel points does not use the interconnections between the points as found in the feature extraction phase. The points are connected by triangulations based upon a different criterion. If the ridge and channel lines were preserved in the original triangulation, it is possible that many of the points used in the triangulation would become unnecessary.

Second, the point addition procedure does not examine all grid points in a triangle to find the point that should be added. Instead, only some points, regularly scattered in the triangle, are tested. This heuristic method, which was used to save money in TIN construction process, can be eliminated. A trade off can be arranged in which preprocessing time is traded against performance, especially for repeated use.

Lastly, the present technique selects points using a threshold that is globally determined. A point differing by 5 m from a triangle with steep gradient is considered as important as one in which the local gradient is low. We conjecture that a procedure more sensitive to local context, perhaps by precalculating a local measure of convexity, would noticeably improve the efficiency of the TIN construction process.

In addition to the possible improvements in the TIN modeling system that are noted above, the current structure for storing the TIN DB can be improved. The present system stores all pointers to neighboring points. Thus, for each pair of points, two pointers are stored; one from the first to the second, and the other from the second to the first. This represents redundant information because we need only one of these pointers to connect the two points as neighbors. Thus, an alternative method of storing the TIN DB is to store only those pointers that represent edges between points lower (in storage order) to those higher (in storage order). This approach could reduce the storage requirements from 19 x N to 13 x N,

a reduction factor of 68 percent. However, this method of storage will affect the computer resources required to use the DB in solving given applications problems. It is estimated that this effect can be reduced sufficiently by proper modifications of the applications algorithms so that the single pointer scheme can be made an effective method of TIN DB storage. However, because we did not analyze this issue in this study, we have used the storage formula of 19 x N.

B. Recommendations

The limitations outlined above suggest that several research tasks should be undertaken to improve our ability to evaluate the TIN model in comparison with other digital terrain models. Specific recommendations are as follows:

(1) Implement and test the refinements to the TIN modeling process, as outlined above, to improve the efficiency and fidelity of the TIN construction process.

(2) Develop a method of generating a family of TIN models for a given terrain region and subject to comparative evaluation in order to assess the ability of competing DTMs to perform within the required error measure ranges.

(3) Make a comparative evaluation of additional terrain regions to improve our understanding of the expected average performance of TIN over a range of more representative terrain regions.

(4) Make a comparative evaluation of additional tactical test problems, e.g., the generation of fire-support coverage maps and the solution of specific point-to-point accessibility problems.

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